

DEMONSTRATION REPORT

UXO Characterization in Challenging Survey Environments Using the MPV

MPV Study at Tobyhanna Army Depot Fuds, Pennsylvania

ESTCP Project MR-201228

JANUARY 2018

Stephen Billings
Black Tusk Geophysics, Inc.

Distribution Statement A
This document has been cleared for public release



Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 01/31/2018			2. REPORT TYPE Demonstration Report		3. DATES COVERED (From - To) 9/30/2012 - 3/30/2018	
4. TITLE AND SUBTITLE UXO Characterization in Challenging Survey Environments Using the MPV MPV Study at Tobyhanna Army Depot Fuds, Pennsylvania					5a. CONTRACT NUMBER Contract: 12-C-0076	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Stephen Billings					5d. PROJECT NUMBER MR-201228	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Black Tusk Geophysics, Inc 1755 West Broadway, Suite 401 Vancouver, BC V6J 4S5 Canada					8. PERFORMING ORGANIZATION REPORT NUMBER MR-201228	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 17D03 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR-201228	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution A: unlimited public release						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The Man-Portable Vector (MPV) technology was demonstrated at the Tobyhanna (TB) Army Depot FUDS site in Pennsylvania in August-September of 2015. The objective of the project was to test detection and classification with portable systems at a densely forested site as part of the ESTCP Live-Site Program for Munitions Response, funded here under ESTCP MR-201228.						
15. SUBJECT TERMS UXO, Unexploded Ordnance, Survey, MPV, Munitions Response, Attitude and Heading Reference Sensor, Data Acquisition Digital Geophysical Mapping						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Stephen Billings	
UNCLASS	UNCLASS	UNCLASS	UNCLASS	59	19b. TELEPHONE NUMBER (Include area code) 720-306-1165	

Page Intentionally Left Blank

Table of Contents

List of Figures	iii
List of Tables	iii
Acronyms	iv
ACKNOWLEDGEMENTS	v
EXECUTIVE SUMMARY	vi
1. INTRODUCTION	1
2. TECHNOLOGY	2
2.1 MPV TECHNOLOGY DESCRIPTION	2
2.2 TECHNOLOGY DEVELOPMENT	5
2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY	5
3. PERFORMANCE OBJECTIVES	7
3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION	8
3.2 OBJECTIVE: STATION SPACING IN DETECTION MODE	8
3.3 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS	9
3.4 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST	9
3.5 OBJECTIVE: CUED INTERROGATION OF ANOMALIES	9
3.6 OBJECTIVE: PRODUCTION RATE	10
3.7 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI	10
3.8 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI	10
3.9 OBJECTIVE: MINIMUM NUMBER OF UNCLASSIFIABLE ANOMALIES	11
3.10 OBJECTIVE: CORRECT ESTIMATION OF LOCATION AND DEPTH	11
4. SITE DESCRIPTION	12
4.1 SITE SELECTION	12
4.2 BRIEF SITE HISTORY	14
4.3 MUNITIONS CONTAMINATION	14
4.4 SITE GEODETIC CONTROL INFORMATION	15
5. TEST DESIGN	16
5.1 DEMONSTRATION SCHEDULE	16
5.2 SYSTEM SPECIFICATION	17
5.3 INSTRUMENT VERIFICATION	17
5.4 DATA COLLECTION PROCEDURES	18
6. DATA ANALYSIS	22
6.1 PREPROCESSING	22

6.2	TARGET SELECTION FOR DETECTION	24
6.3	PARAMETER ESTIMATION	26
6.4	TRAINING.....	26
6.5	CLASSIFICATION	26
7.	PERFORMANCE REVIEW	28
7.1	PRODUCTIVITY	28
7.2	IVS REPEATABILITY	29
7.3	CLASSIFICATION WITH CUED DATA	31
7.4	POSITIONING ACCURACY	35
8.	COST ASSESSMENT.....	36
9.	MANAGEMENT AND STAFFING.....	38
10.	REFERENCES	39
11.	Appendix A: Health and Safety Plan (HASP).....	40
12.	Appendix B: Points of Contact	41
13.	Appendix C: Root Cause Analysis for a missed seed in the MPV detection study.....	42

List of Figures

Figure 1: The MPV3 deployed with laser positioning in detection mode.	3
Figure 2: MPV3D in cued interrogation mode with 3D coils.	4
Figure 3: MRS-R04A (West) with Operational Grids.	13
Figure 4: MRS-R04A (West) with Revised Demonstration Area Boundary.	13
Figure 5: MRS-R04A (West) Representative Site Photos.	14
Figure 6: Typical target response when the MPV head is placed directly above a buried target.	20
Figure 7: Raw prism locations for East grid for 100% coverage survey.	22
Figure 8: Raw prism locations for West grid.	23
Figure 9: Example of positioning interpolation along a 30 m survey line with RTS dropouts.	24
Figure 10: Detection map for the East grid. Black crosses indicate anomaly pick locations.	25
Figure 11: Detection map for the West grid. Black crosses indicate anomaly pick locations.	26
Figure 12: Standard format of prioritized anomaly list for an ESTCP demonstration.	27
Figure 13: Productivity shown as function of recording of EM data files.	28
Figure 14: Histogram of the normalized peak amplitude for each IVS pass over each target.	29
Figure 15: Recovered polarizability decay curves illustrating repeatability of IVS cued data.	30
Figure 16: Stability of the recovered size parameter for cued IVS data.	30
Figure 17: ROC curve for stage 1 dig list.	31
Figure 18: Example of ground truth report for items ranked 11 to 15 in the dig list.	32
Figure 19: Pick, dig and predicted locations for nearby targets TH-10635 and 10655.	33
Figure 20: Positioning offset between pick and dig locations reported in ground truth file.	34
Figure 21: MPV classification ROC curve with corrected ground truth at Tobyhanna.	34
Figure 22: Project management organization for the demonstration.	38
Figure 23: Gridded data for Z-component of the 0.95 ms time channel around missed seed	43
Figure 24: Signal for Z-component data at channel t_9 (0.95 ms) on line profile going through seed location.	43
Figure 25: Detection modeller results for the MPV above a small ISO schedule 80	45
Figure 26: Maximum signal amplitude among all MPV receivers as a function of the sensor location.	46
Figure 27: Tobyhanna East grid. View from IVS on South edge of grid towards the Northwest corner.	46

List of Tables

Table 1: Performance Objectives.	7
Table 2: Demonstration steps and schedule.	16
Table 3: Cost model for the MPV demonstration.	36
Table 4: Points of Contact for the MPV Demonstration.	41

Acronyms

AHRS	Attitude and Heading Reference Sensor
BTG	Black Tusk Geophysics, Inc.
BUD	Berkeley UXO Discriminator
cm	Centimeter
CO	Colorado
CRREL	Cold Regions Research and Engineering Laboratory (ERDC)
DAQ	Data Acquisition System
DGM	Digital Geophysical Mapping
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
HASP	Health and Safety Plan
IDA	Institute for Defense Analyses
IVS	Instrument Verification Strip
m	Meter
mm	Millimeter
MPV	Man Portable Vector
ms	Millisecond
MR	Munitions Response
MRS	Munitions Response Site
NH	New Hampshire
NI	National Instrument
NRL	Naval Research Laboratory
PI	Principal Investigator
PLS	Public Land Surveyor
POC	Points of Contact
RCA	Root Cause Analysis
RTS	Robotic Total Station
s	Second
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SOP	Standard Operating Procedure
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
TOAR	Tobyhanna Artillery Range
TOI	Target of Interest
UXO	Unexploded Ordnance

ACKNOWLEDGEMENTS

The MPV demonstration at Tobyhanna Army Depot was funded by the Environmental Security Technology Certification Program, project MR-201228. The MPV originated with the work of Kevin O'Neil and Benjamin Barrowes from the Engineering Research and Development Center (ERDC) at the Cold Regions Research and Engineering Laboratory (CRREL) in Dartmouth, New Hampshire and David George of G&G Sciences, who has been fabricating all generations of MPVs. The original project was supported by the Strategic Environmental Research and Development Program (SERDP) project MM-1443.

This report was compiled by Nicolas Lhomme, project geophysicist in charge of planning and executing the data collection, processing the data for detection and classification, and writing up results. Data collection also involved Laurens Beran, Leonard Pasion and David Sinex from BTG, and support from CH2MHill's Vicki Rystrom. The report was reviewed by Beran and Billings. Data processing and analysis was performed with the UXOLab software package, BTG's custom MatLab-based software for advanced classification.

EXECUTIVE SUMMARY

The Man-Portable Vector (MPV) technology was demonstrated at the Tobyhanna (TB) Army Depot FUDS site in Pennsylvania in August-September of 2015. The objective of the project was to test detection and classification with portable systems at a densely forested site as part of the ESTCP Live-Site Program for Munitions Response, funded here under ESTCP MR-201228.

The MPV is a handheld electromagnetic induction (EMI) sensor designed for munitions detection and classification with a form factor that offers enhanced portability and ruggedness relative to cart-based systems. The sensor head comprises of a 0.5-meter diameter disk that includes a vertical field transmitter and a square array of four vector receivers that measure the three-orthogonal components of the induced field. The MPV supports full coverage, dynamic data collection along survey lines to map metallic targets, as well as classification of these targets. Classification can be applied to dynamic data, or to high quality static data obtained by revisiting selected targets for cued interrogation. In this survey mode, a detachable set of two orthogonal, horizontal-axis transmitter coils is placed on top of the MPV head to generate transverse excitation of buried objects. The technology has been demonstrated at six sites within the ESTCP projects MR-201005, 201158 and 201228: Yuma Proving Ground, Camp Beale, Spencer Range, George West, New Boston and Waikoloa. These past sites spanned multiple environmental conditions, including open field, dense forests, steep sided hills, boulder fields, strong geologic noise background, high target density and a wide range of munitions types.

The Tobyhanna site was chosen to test the state of the art for positioning and classification in a dense forest and assess spatial coverage, accuracy and productivity. The MPV and TEMTADS were both tested on two half-acre grids, using the same detection line layout with 0.5 m spacing and the same Robotic Total System (RTS) laser ranger system. For the MPV, the prism was mounted at the top of the sensor boom, 1.2 m behind and 2 m above the MPV head. This offset was advantageous for this site because the MPV could be rotated to maintain or regain line of sight between the RTS and prism. This ensured accurate positioning over a large portion of the site. The MPV's manoeuvrability also helped get close to tree trunks and under branches to maximize coverage. The daily detection coverage rate was approximately 0.2 acres, less than the 0.5-0.7 acres achieved with GPS positioning in open fields. The slower survey was due to time lost moving the base station to avoid trees, stopping along lines to regain line of sight, and delays to avoid interference with the TEMTADS. Productivity for cued interrogation was typical for the MPV, averaging approximately 150 anomalies per day.

Data processing was complicated by the need to interpolate data over positional gaps. One seeded target was initially missed due to overly-aggressive target selection criteria. The revised target list captured all seeds and contained 516 targets, versus 430 targets for the TEMTADS, with 170 common targets within 0.3 m and 230 within 0.4 m. The MPV had more targets due to higher coverage rate and greater sensitivity to small targets by being closer to the ground.

All targets were cued with the MPV, whereas classification was performed on the subset of targets that had been excavated, which included all TEMTADS targets and 68 MPV specific targets. Classification results revealed issues with the ground truth related to reporting target labels and categories. After resolving these issues, the dig list was re-scored, all TOI were found while rejecting 83% of the clutter. Positional accuracy was satisfactory despite the challenging environment; the median positioning error for TOI was 16 cm at the picking stage and 14 cm at the classification stage. Overall the demonstration was successful at meeting all but two of the identified performance objectives.

1. INTRODUCTION

The Environmental Security Technology Certification Program (ESTCP) organized a demonstration of classification technologies for Munitions Response (MR) at Tobyhanna (TB) Army Depot in Pennsylvania in August-September of 2015. This demonstration was designed to investigate classification performance at a live site that challenged the existing technology and was part of an ongoing effort to characterize where and how classification could be applied. The Tobyhanna site was covered with a dense forest that precluded 100% coverage for detection surveys and obstructed GPS communication. The staging area was determined after a transect study that identified an area with potential munitions contamination. Prior to the ESTCP demonstration, the area was cleared of underbrush, leaving all trees larger than 2-3 inches in diameter, and seeded with inert munitions.

The study presented in this document is a demonstration by Black Tusk Geophysics (BTG) of the detection and classification capabilities of the Man Portable Vector (MPV) sensor and a laser positioning system that was applied for the first time with the MPV at a live site. The MPV is an ESTCP-funded electromagnetic induction (EMI) sensor that was designed to extend advanced classification capabilities to sites with challenging surveying conditions. The system was utilized to detect metallic targets in dynamic mode and to classify detected objects with high-quality, cued interrogation data. The MPV was tested alongside the Naval Research Laboratory (NRL) Time Domain Electromagnetic Towed Array Detection System (TEMTADS) instrument, for direct comparison at a challenging site with a common set of detected objects. The TEMTADS was operated by a team from CH2MHill (CH2M), who coordinated the project.

2. TECHNOLOGY

The MPV technology is an electromagnetic induction sensor using transmitter coils and an array of vector receivers in a handheld form factor. The sensor presented in this study is the third-generation prototype MPV.

2.1 MPV TECHNOLOGY DESCRIPTION

2.1.1 Electromagnetic sensor

The MPV is a handheld EMI sensor. This sensor is specifically designed to (1) acquire data that supports classification of unexploded ordnance (UXO), (2) be man portable and therefore easy to deploy and maneuver, and (3) be sufficiently rugged for intensive field use. The main EMI sensing components are a transmitter coil and an array of five vector receiver units (cubes) that measure the induced EM field (Figure 1). The EMI components are contained in the sensor head, which is a circular plastic enclosure with 50-centimeter (cm) diameter and 8.5-cm height. The circular transmitter coil is wound around the disk while the receiver cubes are distributed in a cross pattern inside the disk. While the main sensor head only has a vertical-axis transmitter loop, it can be augmented with a pair of orthogonal horizontal-axis transmitter loops. These are packaged as detachable rectangular shaped coils that can be placed on top of the main sensor head (Figure 2). Their main purpose is for the cued interrogation mode, where they help provide transverse excitation of a buried object of interest¹. This configuration is called the MPV3D and could be regarded as a man-portable version of the Geometrics MetalMapper. The MPV's transmitters intermittently illuminate the subsurface with a primary magnetic field. When a transmitter is turned off, the receiver cubes measure the three orthogonal components of the transient secondary field radiated by buried metallic objects. Each receiver cube is comprised of three air-induction 8-cm square coils, and the use of multiple receiver cubes generally improves the recovery of target parameters for classification. The MPV is controlled by a new set of compact, custom-made G&G Sciences transmitter, receiver and filter boards, and a Compact National Instrument (NI) data acquisition system (DAQ) that digitizes the measured signal. The new DAQ weighs one third of the original one, consumes approximately 70% less battery energy and operates with a single lithium-ion battery.

The MPV is a handheld sensor. The sensing unit weighs approximately 11.6 kg, including 5.3 kg for the sensor head, 0.6 kg for the control display (Panasonic ToughPad) and 5.7 kg for the handles and cables (excluding GPS rover or laser prism). The new DAQ weighs 6.5 kg with one battery; it is generally mounted on a light, plastic framed backpack that the main operator can carry (Figure 1, top right). The backpack features adjustable straps with carabiners that clip to the MPV handle to help support its weight in dynamic mode. The horizontal field transmitter coils required for cued interrogation add 5 kg to the sensing unit. The horizontal coils can remain affixed to the sensor head when moving between cued locations.

¹ In past demonstrations the sensor head had to be placed at a series of 4-5 secondary locations around an anomaly to generate that transverse excitation, introducing complications of increased separation between the receivers and the buried object, the requirement for high-accuracy positioning and the complexity of defining the appropriate secondary locations and interpreting the responses.



Figure 1: The MPV3 deployed with laser positioning in detection mode.

Left: The sensor head is an 8.5-cm thick disk that contains a circular transmitter and five 3D receiver cubes distributed in a cross pattern. Sensor positioning in a forest is achieved with a laser system that locates a prism mounted on the top end of the sensor handle (yellow mast) and with an orientation sensor (small orange box at base of mast). **Top right:** The data acquisition system and batteries are mounted on a backpack frame that the main operator can carry. **Bottom right:** A touch-screen computer is used to control survey parameters, trigger acquisition events, and store the data. The display can be set to provide real-time data feedback, e.g. the pictured screen shows the predicted target location for a nearby target while in detection mode (blue dot on black panel) as well as other information (signal decays on the lower right, position and orientation data on the upper right table and acquisition controls on the top left).

The duration of the transmitter excitation and the duration of the receivers recording of the targets response time decay are adjustable to accommodate the specific needs of target detection and classification. Ideally, the highest quality data is acquired when the sensor is static, so that multiple cycles of target excitation and time-decay response can be repeated and averaged (stacked) to reduce the effect of transient noise sources. A full cycle corresponds to two transmit-receive sequences with the transmitter current firing in opposite directions. Use of long transmit-receive cycles can be applied to capture the time decay rate of the target response, which relates to the target type and can help distinguish between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007). These effects can be captured with 8.3 milliseconds (ms) or 25 ms time decay, which correspond to cycles of 33 ms or 100 ms. Cued interrogation with the MPV generally uses a 25 ms time decay, repeating multiple transmit-receive cycles for 10 s and averaging across transmit-receive cycles. In detection mode, the sensor is moving and collecting dynamic data. To avoid distortion of the signal, the distance traveled while the sensor is transmitting and receiving should be minimal. This can be achieved by using shorter transmit-receive cycles. To limit the volume of data storage, and to match the update rate of positional

systems, the data are saved every 0.1 s at discrete locations, similar to a series of cued measurements. There is a tradeoff between the duration of a transmit-receive cycle and the number of cycles than can be done within a 0.1-s interval. Long cycles are better for characterizing targets and environmental noise, whereas short cycles can be repeated multiple times and averaged to reduce the effect of noise. Depending on the targets of interest and site conditions we use 2.8 or 8.3 ms time decay, which allows stacking 9 or 3 cycles, respectively. The default setting for dynamic data is 2.8 ms decay.



Figure 2: MPV3D in cued interrogation mode with 3D coils.

The MPV user interface has real-time data monitoring capabilities. The recorded data can be displayed to verify data quality and identify potential issues such as the presence of magnetic soil or a damaged receiver. The past and present sensor location can be displayed on a map along with preset survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields either with arrows (the so-called “dancing arrows”) or with the real-time dipole inversion (lower right panel in Figure 1). Cued data are inverted in near real-time and the target location, depth and polarizability decays can be displayed. These features assist the field operator in efficient data collection and provide some immediate quality control. This capability could in principle also enable alternative deployment modes, where detection and classification data could be collected as part of the same survey, thus limiting the need to revisit an anomaly for further characterization.

2.1.1 Positioning in a wooded environment

Accurate positioning is required for detection and classification. Dense forest and thick canopy precluded use of standard GPS at Tobyhanna. Instead, we used a Robotic Total Station (RTS) equipped with a laser gun and an automatic tracking system to follow a moving prism mounted at the top end of the MPV sensor handle (Figure 1). The RTS can predict the prism location relative to the base, which is placed at a geographically referenced location. The RTS was used to locate the MPV until there were too many tree obstacles blocking line of sight between the RTS and the prism. At that point the RTS was moved to another referenced location so that the prism could be tracked over the next part of the site.

2.2 TECHNOLOGY DEVELOPMENT

The MPV technology development began in 2005 with a project led by Drs. Kevin O'Neill and Benjamin Barrowes with the Cold Regions Research and Engineering Laboratory of the Engineering Research and Development Center (CRREL, ERDC) in Dartmouth, New Hampshire (NH) and was funded by the Strategic Environmental Research and Development Program (SERDP) under the contract MM-1443 (Barrowes et al., 2007). This first MPV prototype was built in 2005-2006 by David George of G&G Sciences, Grand Junction, Colorado (CO). In 2008 the current BTG team started field trials to assess the quality of MPV static and dynamic data for classification, study the effect of magnetic soils and test the positioning system. We found that the particular geometric design of the MPV could be used to defeat some of the adverse soil effects. The original positioning system, the ArcSecond laser ranger, was found to be impractical. It was replaced with the beacon, a local positioning system. In 2009 the sensor head was redesigned with lighter materials and a smaller head diameter to reduce weight and improve manoeuvrability and ruggedness while maintaining its expected performance (Lhomme, 2011).

The MPV entered the ESTCP program in 2010 with the MR-201005 project led by Nicolas Lhomme of Black Tusk Geophysics. Fabrication of the second-generation MPV was completed and the technology was validated at the Yuma Proving Ground UXO test site in October 2010. The technology was then tested at the former Camp Beale in June 2011 to demonstrate cued interrogation and classification in open field and in a moderately dense forest. In the follow-on ESTCP project MR-201158, the MPV was first demonstrated at Spencer Range, TN in June 2012 with detection and dynamic classification in open field and cued interrogation only in a forest, and then at former Camp George West, CO in October 2012 on the side of a mountain with slopes up to 40%. In this ESTCP project MR-201228, the technology was tested in a dense forest at the New Boston Air Force Station in August 2013, and at a site with rocky outcrops and strong geological background at Waikoloa, Hawaii in January 2014. The concept of using additional transmitters for cued interrogation was demonstrated on a subset of the Waikoloa targets, prompting adoption of this simpler survey mode for the Tobyhanna demonstration. A new sensor head was fabricated in 2015 to prepare the system for commercialization, using sturdier material and a detachable handling boom, while retaining the same dimensions and using new receivers with improved sensitivity. The DAQ was replaced with a compact DAQ that was lighter than the previous DAQ and used less power.

2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY

The MPV offers several key benefits:

- Hand-held form factor. The MPV is the only handheld advanced EMI sensor developed

under the SERDP-ESTCP program. This form-factor enables surveys at sites where terrain and vegetation preclude use of heavier, cart-based systems. The MPV's portability can improve productivity in rough terrain. In contrast, existing "man portable" systems with classification capabilities (e.g., Geonics EM63, TEMTADS2x2) must be mounted on a cart or litter platform due to the size and weight of the multiple coils of wire required for the transmitters and receivers. The lightweight MPV sensor and electronics can also be affordably and easily transported;

- Five receivers simultaneously record three orthogonal components of EM field with near-perfect relative positioning among receivers. The multi-component, multi-static design reduces number of soundings for target characterization;
- Magnetic soil noise effect can be detected and mitigated. The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil through techniques developed in SERDP MM-1414 and MM-1573;
- Fully configurable through acquisition software. A graphical interface can be used to set acquisition parameters such as transmitter waveform characteristics, duration of excitation, number of measurement cycles, stacking and recorded time channels;
- Stable EMI components: Receivers have imperceptible measurement drift and are largely insensitive to survey conditions. Measure data can be readily modelled using standard EMI theory;
- High resolution: Having several relatively small receivers (8-cm coils) allows localization and differentiation of individual anomalies better than large receivers (e.g., EM61), that tend to "smear out" secondary fields.

The MPV's portability introduces some limitations for detection and classification: the smaller footprint necessitates tighter line spacing and the reduced transmitter size limits the depth of investigation relative to larger systems. The goal of these demonstrations is to define the limits of this technology.

3. PERFORMANCE OBJECTIVES

This project includes data collection in dynamic detection mode and cued interrogation mode, and data analysis for evaluation of the MPV technology. The specific objectives for each stage are detailed in Table 1.

Table 1: Performance Objectives.

Performance Objective	Metric	Data Required	Success Criteria	Result
Data Collection Objectives				
Spatial coverage in detection survey	Extended footprint coverage	<ul style="list-style-type: none"> • Mapped survey data 	100% at 0.7 m line spacing with intended 0.5 m line spacing, excluding obstacles and hazards	Pass
Station spacing	Distance between soundings	<ul style="list-style-type: none"> • Sensor location 	$98\% \leq 0.25 \text{ m}$; no gaps $> 0.4 \text{ m}$ except obstacles or hazards	Pass
Repeatability of Instrument Verification Strip (IVS) survey	Amplitude of EM anomalies and amplitude of polarizabilities	<ul style="list-style-type: none"> • Twice-daily IVS survey data 	Factor 2 on detection amplitude and 1.5 on target size	Pass
Detection of all targets of interest (TOI)	Percent of seeded items detected	<ul style="list-style-type: none"> • Location of seeded items • Anomaly list 	100% of seeded items detected within 0.5 m halo	Data: Pass Analysis: Fail (one seed initially missed)
Cued interrogation of anomalies	Instrument position	<ul style="list-style-type: none"> • Cued data 	100% of anomalies where center of cued pattern is located within 0.5 m of anomaly pick	Pass
Production rate	Acreage and number of cued interrogations	<ul style="list-style-type: none"> • Log of field work 	Detection: 0.4 acre/day Cued mode: 150 anomalies/day	Detection: Fail (0.2 acre/day) Cued: Pass (150 anom./day)
Analysis and Classification Objectives				
Maximize correct classification	Number of TOI retained	<ul style="list-style-type: none"> • Ranked dig list • Scoring reports by IDA 	Approach correctly identifies 100% of TOI	Pass
Maximize correct classification of non TOI	False alarm rate (FAR)	<ul style="list-style-type: none"> • Ranked dig list • Scoring reports by IDA 	Reduction of clutter digs by 50% for 100% TOI	Pass (83% clutter rejection)
Minimize number of unclassifiable anomalies	Number of "Can't Analyze" for cued data classification	<ul style="list-style-type: none"> • Ranked dig list 	Less than 10% of "Can't Analyze"	Pass (1.5%)

Correct location and depth of TOI	Accuracy of estimated target parameters for seed items	<ul style="list-style-type: none"> • Results of intrusive investigation • Predicted location 	95% TOI with $\Delta Z \leq 0.15$ m , ΔN and $\Delta E \leq 0.25$ m	Pass
-----------------------------------	--	--	---	------

3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION

The dynamic detection survey should cover a maximum of the area of interest so that all detectable targets are illuminated. Targets are detectable if the measured target response is sufficiently strong to exceed a given threshold. Simulations and analysis of field data suggest that there is negligible loss of detectability when a target is located 0.1 m off to the side of the MPV, which corresponds to an effective line spacing of 0.7 m. The intended line spacing is 0.5 m.

3.1.1 Metric

The metric is the spatial coverage of the MPV detection survey, using 0.7 m line spacing, over the entire detection area.

3.1.2 Data requirements

The geographic coordinates for the perimeter of the region to be surveyed and the MPV survey track are utilized.

3.1.3 Success criteria

Success requires 100% spatial coverage with 0.7 m line spacing, excluding obstacles. The calculated coverage is 99.8% on the East grid, including obstacles, and 99.9% on the West grid, including obstacles. The objective is met.

3.2 OBJECTIVE: STATION SPACING IN DETECTION MODE

This objective is meant to ensure that the target response is not being smeared out by an operator moving the sensor head too quickly. The survey speed is enforced through a station spacing requirement.

3.2.1 Metric

The distance between soundings along lines is computed.

3.2.2 Data requirements

The sensor head location is derived from laser and AHRS measurements and is used to compute this metric and map the EMI data.

3.2.3 Success criteria

Success requires that 98% of the data points have at most 0.25 m spacing along line and 100% have less than 0.40 m spacing. The station spacing, after interpolation of locations where the RTS had no coverage, is 99.98% at 0.25 m and 100% at 0.40 m on the East and West grids.

3.3 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS

The reliability of survey data for target detection and classification depends on the consistent performance of the survey equipment. This objective utilizes twice-daily verification on an instrument verification strip (IVS) where metallic targets were buried. The IVS is surveyed in detection mode during the detection survey. The IVS targets are interrogated in cued mode during the entire demonstration.

3.3.1 Metrics

The metric for detection relates to the amplitude of the maximum target response, defined as the norm of the total field on each receiver cube for the 0.5 ms time channel. The metric for cued interrogation is the target size, here defined as the norm of the polarizability components also for the 0.5 ms time channel.

3.3.2 Data requirements

IVS data are recorded for both detection and cued survey modes. A detection map is built and the detection amplitude is computed for each target. For the cued survey the data are inverted and the stability of the recovered target parameters is verified.

3.3.3 Success criteria

The detection requirement is a factor 2 on the target response and a factor 1.5 on the target size parameter for dynamic and for cued data. The objective is met (analysis in section 7.2.1).

3.4 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

High quality data should lead to high probability of detecting all TOI at the site.

3.4.1 Metric

The metric for this objective is the percentage of seed items that are detected using the specified anomaly detection threshold.

3.4.2 Data requirements

The detection list was submitted to CH2MHill for verification that seeds were selected.

3.4.3 Success criteria

The objective was to detect 100% of the seeded items within a 0.5-m radius. One seed was missed. A Root Cause Analysis (RCA) report showed that the seed was clearly detectable in the data, but it was not selected due to over-aggressive target selection criteria (Appendix C).

3.5 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

The reliability of cued data depends on acceptable instrument positioning during data collection in relation to the actual anomaly location.

3.5.1 Metric

The metric for this objective is the percentage of anomaly picks that are located within the acceptable distance to the center of the cued interrogation of each anomaly.

3.5.2 Data requirements

The MPV location is stored during cued interrogation and compared with pick location.

3.5.3 Success criteria

The objective is met if 100% of the selected anomalies have one cued acquisition within the 0.5 m distance of the anomaly pick location. The objective is met.

3.6 OBJECTIVE: PRODUCTION RATE

3.6.1 Metric

The metrics for this objective are the mean daily survey rates in terms of acreage for dynamic survey and number of targets for cued interrogations.

3.6.2 Data requirements

The acreage and number of surveyed anomalies is derived from recorded positions.

3.6.3 Success criteria

The expected mean daily survey rates were at least 0.4 acre for detection and 150 anomalies for cued interrogation. The average daily productivity was approximately 0.2 acre and 150 targets. This low rate was due to use of RTS, which caused delays when prism lock was lost or the base station needed to be moved. Survey days were shorter than expected due to the site remoteness, weather interruptions and delays due to coordination with another sensor (shared space and personnel). The daily production is detailed in section 7.1.

3.7 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

This is one of the two primary measures of the effectiveness of the classification approach. This objective concerns correct classification of TOI.

3.7.1 Metric

The metric for this objective is the number of items on the anomaly list for a particular sensor that are correctly classified as TOI (i.e. identified prior to the final stop dig point) by each classification approach.

3.7.2 Data requirements

The demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. ESTCP personnel used their scoring algorithms to assess the results.

3.7.3 Success criteria

The objective of correctly labelling 100% of the TOI on the ranked anomaly list was met.

3.8 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

This is the second measure of the effectiveness of the classification approach. This objective concerns false alarm reduction.

3.8.1 Metric

The metric for this objective is the number of items on the sensor dig list that can be correctly classified as non-TOI (i.e. identified after the final stop dig point) by each classification approach.

3.8.2 Data requirements

The ranked anomaly list is compared to the ground truth information.

3.8.3 Success criteria

The objective is that more than 50% of the non-TOI items can be correctly labeled as non-TOI while retaining at least 100% of the TOI on the dig list. After correction of ground truth labelling issues, the stop dig point achieved 83% clutter rejection, with the last TOI being found after digging only 7% of the clutter.

3.9 OBJECTIVE: MINIMUM NUMBER OF UNCLASSIFIABLE ANOMALIES

Anomalies for which reliable parameters cannot be estimated reduce the effectiveness of the classification process. These anomalies must be placed in the dig category.

3.9.1 Metric

The metric is the number of anomalies that cannot be analyzed by our data processing methods.

3.9.2 Data requirements

The submitted dig list indicates those anomalies.

3.9.3 Success criteria evaluation and results

The objective is that less than 10% of the cued anomalies cannot be analyzed. Only 1.5% of the anomalies were in this category.

3.10 OBJECTIVE: CORRECT ESTIMATION OF LOCATION AND DEPTH

Correct target classification relies on the capability to extract valid target parameters. Accurate TOI location is also important for safe and efficient site remediation.

3.10.1 Metric

The metric is the difference between observed and predicted depth and geographic location.

3.10.2 Data requirements

Predicted target location and depth are compared to ground-truth validation measurements.

3.10.3 Success criteria

Depth should be recovered within 0.15 m, northing and easting within 0.25 m for 95% of TOI. After addressing some issues with the ground truth information, we found that the depth criterion is valid for 96% of TOI and the distance criterion also for 96% of the TOI.

4. SITE DESCRIPTION

The following section is adapted from the CH2M demonstration plan. The demonstration site is located within Munitions Response Site (MRS) R04A (West) at the Tobyhanna Artillery Range (TOAR) Formerly Use Defense Site (FUDS). The MRS is located within Pennsylvania State Game Lands. The site is used for recreational activities such as camping, hiking, fishing, mountain biking, and snowmobiling. Parts of the MRS are located within a designated natural area open only to passive recreation and hunting. Munitions response actions were on-going within the MRS.

4.1 SITE SELECTION

MRS-R04A (West) encompasses approximately 250 acres and is characterized by densely-wooded, uneven terrain. Figure 3 presents the MRS with the operational grid system used by the current munitions response contractor. Each grid measures 100 ft by 100 ft. The “*revised demonstration boundary*” shown in Figure 3 depicts an approximate 11-acre portion of the MRS, from within 1 acre that had not yet been cleared was selected for the demonstration. Based on historical live-fire training conducted on artillery ranges at TOAR FUDS and the results of a previously-completed Remedial Investigation (RI), this MRS encompassed an impact area. Figure 4 presents an enlarged view of the 11-acre selection area from within which the demonstration grids were identified. This figure also depicts the generalized location of the MRS relative to the TOAR complex. Figure 5 presents photos of the existing site conditions taken by CH2M during a site reconnaissance visit on May 19 and 20, 2015.

CH2M had not been provided information that would enable estimation of subsurface anomaly densities for the MRS. Therefore, CH2M performed a digital geophysical mapping (DGM) survey with the Geometrics G-858 cesium vapor gradiometer (G-858G) along transects extending through the accessible portions of the approximate 11-acre selection area. The nominal transect spacing was 20 ft; however, because no vegetation clearance was performed in advance of the G-858G survey, transect spacing and percent coverage was variable across the 11-acre selection area. The objective of the G-858G survey was to assess relative anomaly density in order to identify candidate grids for the TEMTADS 2x2 and MPV demonstration. Positional data for the G-858G survey was recorded using a Trimble ProXRS differential GPS (DGPS) system with an intended sub-meter horizontal accuracy. A Geometrics G-856 proton precession magnetometer was used as a stationary base station to record ambient magnetic field fluctuations throughout each day of G-858G data collection in order to facilitate evaluation of total field data recorded by each G-858G sensor.

Processing and target selection of the G-858G transect data was performed using Geosoft software. Visual Sample Plan (VSP) (Battelle Memorial Institute, 2015) was used to obtain krigged estimates of anomaly density within the 11-acre selection area. Up to 8 grids were selected for the demonstration. CH2M identified locations within the 11-acre selection area that were sufficiently far apart from each other to facilitate concurrent data collection with the TEMTADS 2x2 and MPV without the risk of the two sensors interfering with each other.

Vegetation clearance was performed in the grids to be surveyed with the TEMTADS 2x2 and the MPV. Trees larger than 6 inches were not to be cut. In addition, CH2M performed a surface clearance of the selected demonstration grids. The surface clearance was performed with the

objective of leaving no more than five pieces of exposed or partially exposed metallic objects exceeding 2 inches in any dimension within a 0.2-acre area.

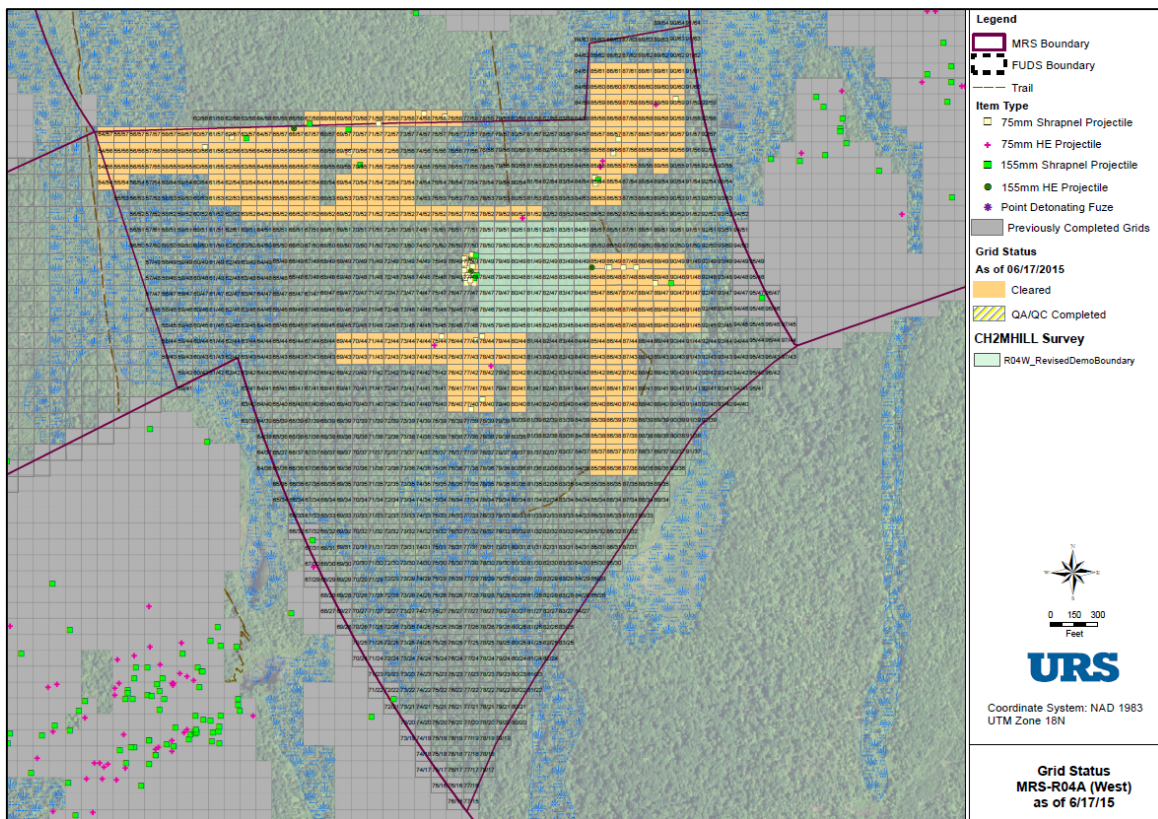


Figure 3: MRS-R04A (West) with Operational Grids

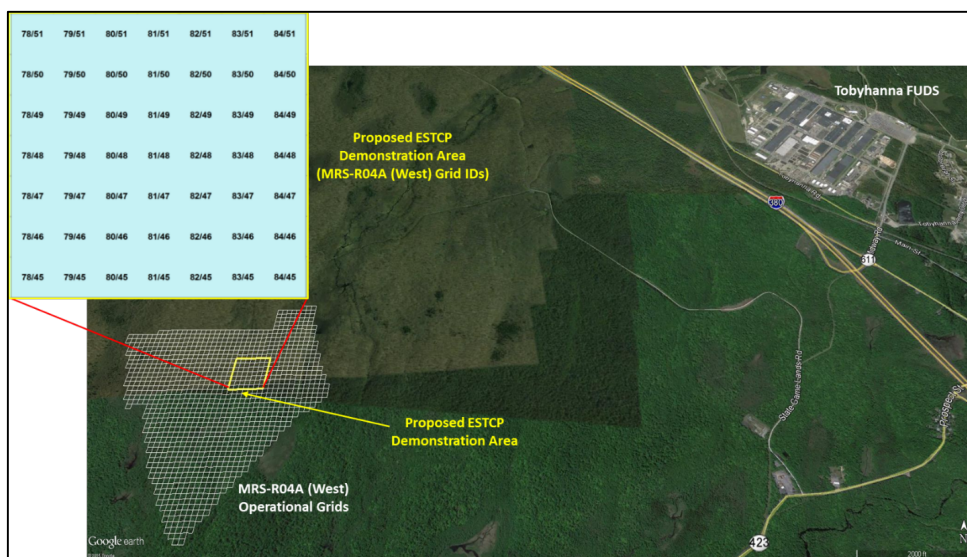


Figure 4: MRS-R04A (West) with Revised Demonstration Area Boundary.



Figure 5: MRS-R04A (West) Representative Site Photos.

4.2 BRIEF SITE HISTORY

Tobyhanna Army Depot was established as Camp Sumerall when the United States purchased thirty-three square miles of property in Monroe County during 1909. The facility was utilized for a variety of missions throughout the years.

The site was first utilized as an area for machine gun and artillery training during 1913. The Army and National Guard used this facility from 1913 until 1949 for field artillery practice. Camp Sumerall was also used as a training area for tanks from July through October 1918. The ranges were the only areas in Pennsylvania where live cannon fire was permitted from 1919 to 1932. During this time frame, the rounds were mainly 75-mm French artillery. The range area between Warnertown and Route 611 became a temporary HQ Explosives Depot. An estimated four million pounds of HE were stored from February 1919 thru October 1919. Bunkers were constructed in the current State Game Lands 127.

4.3 MUNITIONS CONTAMINATION

Suspected munitions within MRS-R04A (West) include primarily 75-mm and 155-mm HE and shrapnel projectiles. However, during the RI conducted within MRS-R04A (West), 37-mm HE projectiles were reportedly recovered along with 75-mm and 155-mm HE projectiles.

4.4 SITE GEODETIC CONTROL INFORMATION

CH2M contracted a Public Land Surveyor (PLS) licensed in Pennsylvania to establish temporary benchmarks for use as control for the RTS during the demonstration. CH2M did not have information on current benchmarks that would be onsite and in use by other contractors working at the site. New temporary benchmarks were established to a third order (1:10,000) accuracy. CH2M utilized Universal Transverse Mercator (UTM) Zone 18 North as the projection. The horizontal datum was North American Datum 1983 (NAD83), CONUS. The vertical datum was North American Vertical Datum 1988 (NAVD 88). All geodetic measurements and reported information were in units of meters. CH2M established additional locations throughout the survey grids with the RTS to maintain line of sight during the TEMTADS 2x2 and MPV surveys.

5. TEST DESIGN

The goal of this study was to demonstrate detection and classification at a densely wooded site and compare MPV performance with a TEMTADS 2x2 study by CH2M. We tested the capability to first perform DGM with accurate mapping and detection of all seeded TOI, then reacquire anomalies of interest and apply classification. Black Tusk and CH2M coordinated their efforts in collecting cued data on a common set of locations. Both studies used the same RTS positioning units.

5.1 DEMONSTRATION SCHEDULE

The demonstration was comprised of data collection and data analysis stages. Upon arrival at the site, the MPV sensor was assembled and tested with the RTS supplied for the study. The MPV was used for the preparation of the IVS in an area where the metallic contamination was negligible and line of sight could be maintained for the RTS to operate without interruption. After laying out guide lines on the ground at 50 cm spacing, dynamic data were collected along lines on both grids, coordinating with the TEMTADS study so that 40 m separation could be maintained between the two EMI sensors.

Table 2: Demonstration steps and schedule.
Stage 2.1 relates to dynamic data and 2.2 to cued data.

Tasks and demonstration timeline	Preparation Calibration			Field surveys			Post survey analysis		
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Mobilization – Demobilization	X					X			
CALIBRATION: Training pit and IVS		X							
CALIBRATION: Inversion and parameters stability analysis of training pit data		X							
CALIBRATION: Twice-daily IVS survey and data analysis			X	X	X				
DYNAMIC SURVEY: Detection survey				X					
DYNAMIC SURVEY: Target picking				X					
CUED SURVEY: Reacquire anomalies					X				
DATA PRE-PROCESSING: Cued data analysis, extract target location for intrusive					X		X		
DATA ANALYSIS: Feature extraction, classification and ranked list							X	X	
RETROSPECTIVE ANALYSIS of intrusive results									X
REPORTING									X

Dynamic data analysis was performed on site so that data quality and positional accuracy could be verified without delay. Anomalies were selected from the dynamic data collected on both grids using a standard target picking approach. All MPV anomalies were subsequently interrogated in cued mode. The cued data provided retrospective feedback on the quality of the dynamic data positioning. Cued data were inverted during the deployment to determine if

recollects were needed. The TEMTADS anomaly list was not available by the time all cued interrogations were completed; therefore the field crew de-mobilized for one week. All TEMTADS anomalies were subsequently interrogated in cued mode.

After digging of a subset of anomalies found in the TEMTADS or the MPV data, the cued data were inverted and classified. The Gantt chart in Table 2 shows the schedule for each phase of the demonstration.

5.2 SYSTEM SPECIFICATION

5.2.1 EMI data acquisition parameters

For cued interrogation mode, the MPV system was set for 25 ms excitation and 25 ms recording of EMI transients. For each of the three transmitters, the full transmit-receive cycle was repeated 33 times and stacked, for a total of 10 s. The data were recorded with 60 logarithm-spaced time gates (10% gate width) from 0-25 ms.

Dynamic data collecting used a short 2.78 ms time window with 9 repeats of the full cycle over a short 0.1 s interval to reduce smearing of the signal by sensor motion.

5.2.2 Positioning and navigation

Positioning in the forest was based on a laser system locating a prism mounted on the MPV, and an attitude sensor to predict the MPV head relative to the prism. A Trimble S6 or S7 robotic total stations with an automatic laser gun was placed at known locations to track an active prism that was mounted on the top extremity of the MPV handling boom, 0.5 m above the head of the MPV operator. The laser system was set to a 3 Hz update rate, the fastest available, while EMI data were collected at 10 Hz.

Azimuth, pitch and roll were measured with an XSens MTi AHRS sensor mounted on the handle and streaming data at 10 Hz. The XSens is a standard fixture for the MPV and has been used in past demonstrations.

5.3 INSTRUMENT VERIFICATION

The IVS was surveyed for calibration, training and sensor verification in dynamic detection and cued interrogation modes. Data were collected on the IVS at the start and end of each day in the collection modes that were used on that day. The dynamic data was analyzed to verify the in-line spacing rate and the stability of the EMI responses. In particular, the amplitude of the target response was analyzed to verify that these were stable, regardless of the operator and the battery levels. The cued data were inverted to recover the static polarizabilities and verify their stability.

Background measurements were acquired every between 10-12 cued anomalies to identify potential variations in the EMI background noise, which at this site were mainly due to the geologic environment. This was done by identifying “quiet” or metal-free areas, using the EM3D onboard dancing arrows and decay curves displays in dynamic mode. The data were subsequently analyzed in UXOLab to confirm the validity of the backgrounds, and to identify any spatial and temporal variability in background noise.

5.4 DATA COLLECTION PROCEDURES

The test site was located in a remote area. Personal vehicles were left on the side of a dirt road, where a shipping container was stored. The actual site was accessed by driving 30 minutes on a rough path with an all terrain utility vehicle. On the first day the equipment was driven into the site to protect the equipment from shocks and damage. The equipment subsequently remained at the site, stored under a tent, for the duration of the study.

The site was divided into an East and a West grid. The IVS was staged next to the East grid, using a control position that could also be used for the East grid dynamic and cued surveys. Given that the MPV and TEMENTADS studies occurred at the same time and that a minimum distance of 40 m had to be maintained between the two systems, the systems were always operated on different grids, and no data would be collected on the East grid while a survey party was collecting data on the IVS. This requirement created numerous delays throughout the survey, especially at the beginning and end of the day, or when one party had to do some troubleshooting that required access to the IVS.

5.4.1 Roles

Field operations involved at least two persons: one to carry the sensor and a second to record field notes, operate the data acquisition software, and operate the RTS positioning controller. During dynamic data collection, the main role of this second person was to verify that the prism was being tracked by the base station and that the MPV sensor head was staying on course and maintaining a close distance to the ground. A third field crew member was occasionally involved to lay out survey lines, take notes, or supply spare batteries.

5.4.2 Detection survey

The MPV sensor head has a diameter of 0.5 m and an effective detection footprint of 0.6-0.7 m. The detection survey was performed by walking along survey lanes, following survey ropes set at 1-m intervals. The operator followed the line with the outer edge of the sensor head, so that the line spacing for the dynamic survey was effectively 0.5 m.

The recommended walking speed for the MPV was 0.5 m/s, with a maximum of 0.8 m/s. This maximum is derived from an empirical rule that the sensor should not move by more than a receiver coil length, here 0.08 m, during the acquisition of a data block, which lasts 0.1 s.

5.4.3 Sample density

In dynamic mode, the sample density is set by the station spacing along line and the receiver spacing across line. The station spacing was approximately 0.05 m on average, whereas the receiver cube separation across track is 0.18 m (the front and back cubes track the center line).

Cued interrogation is based on a single measurement over the anomaly of interest. The sample density is determined by the receiver cube separation between the lateral cubes (right, left, front and back), which is 0.26 m and 0.37 m in the absence of a center cube.

5.4.4 Positioning and navigation

The robotic total station laser positioning system provides local positioning relative to the base station. The base station was placed at a series of locations that were selected to allow full

coverage of the survey area. These base locations were geo-referenced by a professional surveyor.

Prior to collecting dynamic and static data, the survey team determined the most appropriate base station location, then set the base station and covered as much ground as possible with that configuration. During dynamic data collection and while navigating to a cued target location, the operators tried to maintain lock, or line of sight, between the prism mounted on the MPV and the base station. The base station was expected to provide the prism location with centimeter-level accuracy. The following procedure was applied:

- When lock was lost due to an obstacle such as a person or a tree, the base station stopped sending positional updates and automatically searched for the prism for 3 seconds, assuming that the prism was moving at constant velocity and staying on course. The assumption was generally valid as the field crew was instructed to follow straight lines and walk at nearly-constant speed.
- If the prism passed behind a series of obstacles that blocked line of sight, the RTS controller emitted an audio message signalling loss of lock. If the prism was hidden less than 3 seconds, the laser gun would often regain lock with the prism on the other side of the obstacle. The RTS controller would announce that lock had been regained and resume streaming positional updates. All EMI data collected without positional lock was later processed to interpolate positions between valid positional updates.
- If the prism was blocked for longer than 3 seconds, the base station scanned the region where the prism was last seen. The prism was often not found if it continued moving after lock was lost. The field crews were instructed to stop walking as soon as one of the operators, generally the one not carrying the MPV sensor, determined that line of sight was re-established. The MPV sensor was then placed on the ground to identify the new location via constant AHRS readings. The second operator would then use the RTS command to guide the laser gun towards the prism using the joystick or camera. After the RTS controller signalled regained lock, the operators would wait 1 second, and then resume surveying.
- Lines were generally surveyed by walking with the MPV head in front of the operator and the prism following 1.15 m behind the MPV head. Given the offset between the prism and the MPV sensor head, it was often possible for the prism to be placed at a location visible to the laser gun while the MPV head would be hidden by an obstacle. This required moving the prism outside of the survey lane by rotating the prism around the MPV, effectively surveying sideways. The operators were instructed to rotate the sensor head as needed to maintain lock and reduce drops in line of sight. This strategy was also applied when lock was lost. The MPV stopped at a location where the prism was obscured and lock would be regained by rotating the prism around the MPV to a location where the prism could be seen (the MPV would remain at its location, on the ground).

The RTS was also used for navigation to cued anomalies. Locations were pre-loaded into the data acquisition software EM3D, which displays real-time RTS and AHRS information to locate the MPV sensor head relative to a geo-referenced location. Cued locations were approached while maintaining RTS lock. Lock had to be maintained during cued interrogation in order to record a valid position.

5.4.5 Quality checks

Proper operation of the survey sensor was verified every time it was powered on. The positioning systems were checked by moving the sensor and verifying that the position and orientation data shown on the display were updated. The EMI elements were checked by acquiring data in dynamic or static mode, depending on the stage of the project. The operator verified that the "dancing arrows" display was updated in response to variations in the EM environment, that signals were appearing in the time-decay display (Figure 6), and that a .TEM file was being written.

Each battery change was accompanied with a system check, although the DAQ was not necessarily shut down as the DAQ power cables allowed for a hot-swap. A background measurement was acquired in dynamic or static mode before and after the battery swap. The operator monitored the data display for anomalous behavior. The data were later examined on a workstation to identify any sensor drift. In addition, background measurements were acquired every 10-12 anomalies in order to document potential variability in the soil environment and the sensor self-response as power in the batteries drained out.

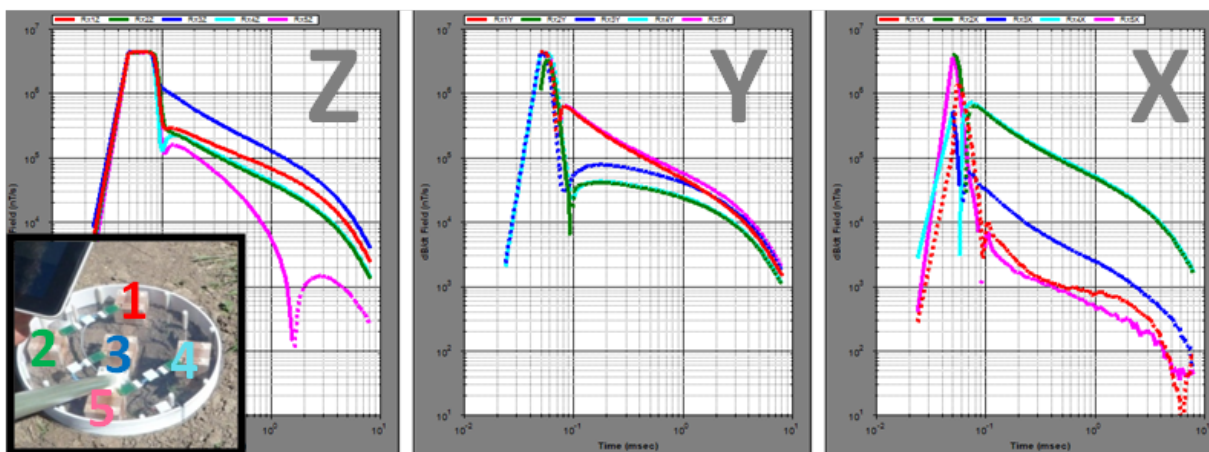


Figure 6: Typical target response when the MPV head is placed directly above a buried target. The Z-component data shows that target is closest to the center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in cube 5 resembles background. The Y data confirm that target is buried between front and back cubes (1, 5) and X data confirm that target is located between side cubes 2 and 4.

During data acquisition, dynamic data were continuously monitored by checking the real-time onscreen feedback to ensure that positional data was updating and survey lines were covered without gaps. EM3D also notified the operator if data errors were encountered (e.g. connection to the DAQ was lost). The second operator, who carried the DAQ backpack, was also involved in quality control by verifying that the sensor operator was keeping the sensor head close to the ground, covering the entire line and maintaining an approximately uniform walking pace.

For cued interrogation, each sounding was displayed immediately after acquisition to verify proper sensor operation and characterization of the buried target. The operator verified that receivers were properly operating by examining data decay curves (Figure 6). An abnormal sounding would generally be hidden (the file was saved and renamed to avoid interrupting the sequence of file names), reacquired at the same location, and recorded in the field notes. If receiver failure occurred the survey would stop until a solution was found. The data were

inverted in near real-time and the predicted target location was shown on the control display. If the predicted offset exceeded 0.2 m the operator relocated the sensor head at the predicted location and took a new measurement. This operation was repeated not more than twice to avoid "chasing" nearby targets that were likely not selected for cued interrogation.

Data quality was also controlled by daily data review and preprocessing of dynamic and cued data. The geophysicist reviewed the data to verify that positioning and EMI sensors were properly functioning, that noise levels were normal, that calculated sensor positions appeared realistic, and that spatial coverage was adequate. Anomalous data were noted and investigated, and the affected survey lines or target locations were resurveyed if needed.

The last check on the cued data was verification that all targets had been visited. This was achieved in the field by looking for measurement marks near picked anomalies on the control display map. The locations for all picked and cued anomalies were later matched by importing the data and comparing positions and labels.

5.4.6 Data handling

Data were stored as .tem files on the DAQ and converted to .CSV files for processing. The data were stored as .TEM and .CSV files on the DAQ and copied on a portable hard-disk drive and on the computers that were used for reviewing the data.

Operators took notes of target names and file numbers in addition to any remarks made by the principal operator in a field logbook. Notes were digitized every day by taking pictures of the notes and filling out a spreadsheet that was used for importing data and quality control.

6. DATA ANALYSIS

6.1 PREPROCESSING

Data streams from the sensor head, the attitude sensor and RTS were written to binary .TEM files, which were later converted to .CSV format without any data alteration. The files were later verified, renamed by appending the target label, and organized for delivery and distribution.

The detection data were merged by synchronizing the different data streams and combining the AHRS and RTS data to predict the receiver locations. The raw prism locations for the East and West grid are shown on Figure 7 and Figure 8. Shadow zones in these images are caused by obstructions (trees), where no prism locations were recorded. Some lines also appear to be missing because the MPV was carried sideways to maintain lock on the RTS prism.

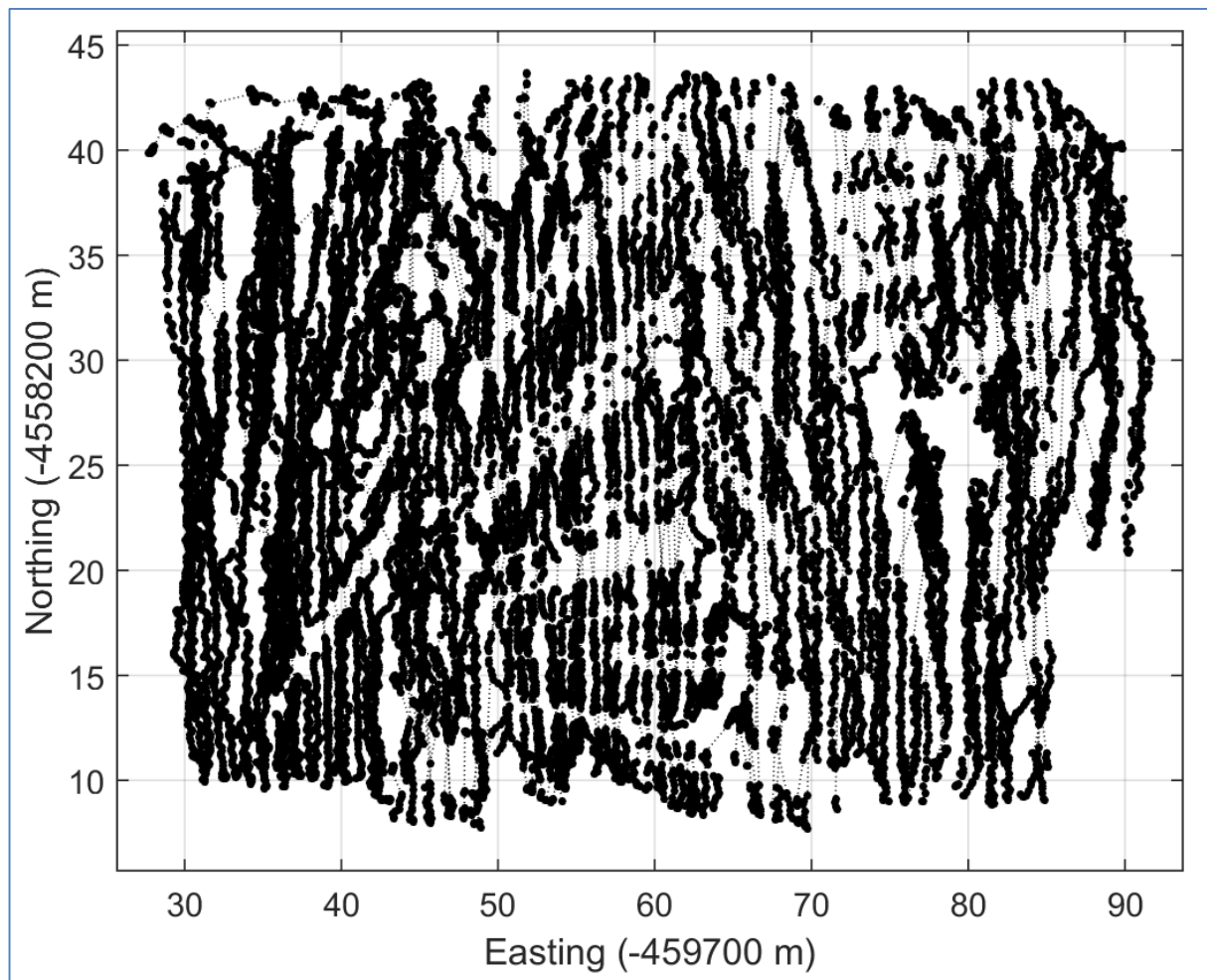


Figure 7: Raw prism locations for East grid for 100% coverage survey.
100% coverage is achieved after interpolation (thin dotted lines indicate loss of RTS lock along line).

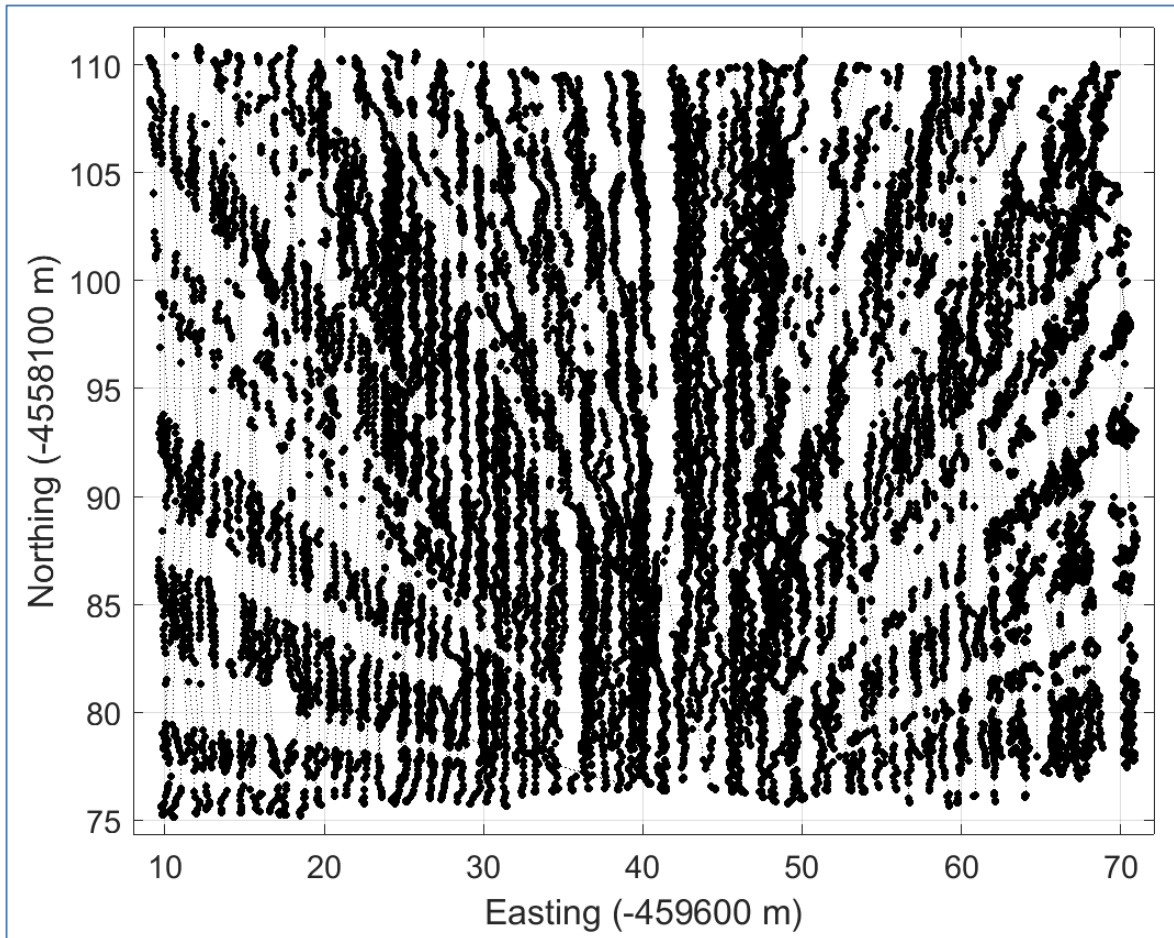


Figure 8: Raw prism locations for West grid.

Foliage caused large shadow zones along lines, where the prism was hidden for more than 3 seconds and was not immediately recovered when exiting the shadow. In these cases lock was lost until the prism was being placed in the line of sight.

To process data acquired without RTS lock, there were three options:

1. Discard all the data acquired in the obscured zone;
2. Linearly interpolate the data as a function of time between the two valid locations. This approach yields unreliable positions because it assumes the sensor is moving at a constant velocity while there is no RTS lock. In reality, the sensor was stationary for at least some of this time while the operators reacquired RTS lock;
3. Identify when the sensor is not moving and only interpolate data over the corresponding time range.

Our method for interpolating positions in RTS gaps was based on this last option, and is illustrated in Figure 9. After losing lock behind obstacles, the operators stopped and placed the sensor on the ground so that the recorded attitude (i.e. pitch) remained constant while lock was reacquired. This stationary IMU data allowed us to identify times where the sensor was not moving during RTS gaps. Once the prism was regained, the first RTS update would

often be an invalid repeat of the last known location (see red outlier points in Figure 9). The subsequent RTS update was a valid prediction of the prism location and indicated the location of the MPV sensor head at the end of an RTS gap. The MPV locations were then interpolated between valid RTS positional updates, using the times between the last update and the stoppage inferred from IMU data. All data between the inferred stoppage time and the new RTS update were associated with a stationary location. This strategy was used to interpolate data over the numerous gaps that were encountered at this site.

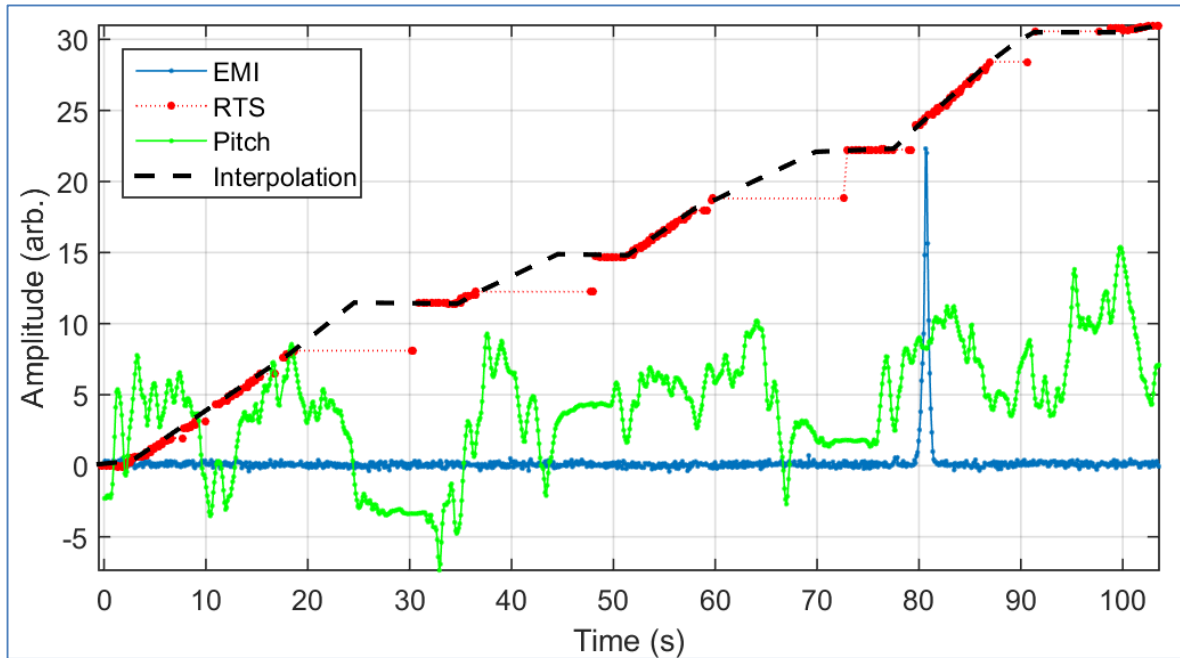


Figure 9: Example of positioning interpolation along a 30 m survey line with RTS dropouts. The red dotted line indicates RTS positions (Northing). There are multiple instances of gaps, where the prism is lost and regained in motion (at times 8, 10, 15, 58, 78, 87 and 91 s) and when it is lost and the survey was paused at a static location to regain lock (between times 19-30, 36-48, and 60-73 s). The green line indicates the sensor pitch: it is nearly constant when the survey stops at a location to regain lock. The black dashed line indicates the interpolated positions: constant positions coincide with nearly constant pitch recordings. The blue line shows the signal for one MPV receiver along the line.

All EMI data were normalized to a unit transmitter excitation by dividing the receiver data by the maximum current amplitude of the associated transmitter to compensate for fluctuations in transmitter battery power. Cued data pre-processing consisted of verifying that the acquisitions were within 0.3 m of the picked anomaly location. Background measurements were analyzed to define the background response to be subtracted from the cued interrogation data.

6.2 TARGET SELECTION FOR DETECTION

The selection of detection parameters was based on the site noise characteristics. A relatively late channel (0.95 ms) was chosen to screen out fast decaying clutter. The predicted detection threshold at this channel for a small ISO Schedule 80 buried at 0.3 m below the ground surface is 0.30 mV/A. This calculation was made using the Detection Modeller program developed under SERDP MR-2226. Given that the noise level for the selected channel was 0.07 mV/A, a

detection amplitude of 0.30-0.35 mV/A satisfied the empirical requirement of picking at approximately five times the noise level. The original target selection required that the threshold be exceeded on two receivers. That criterion proved to be too aggressive as one seed was missed with this approach. This required a root cause analysis (RCA) report, here included in Appendix C. The data were subsequently reprocessed, picked locations were altered and additional picks were added. Detection maps and picks are shown in Figure 10 and Figure 11.

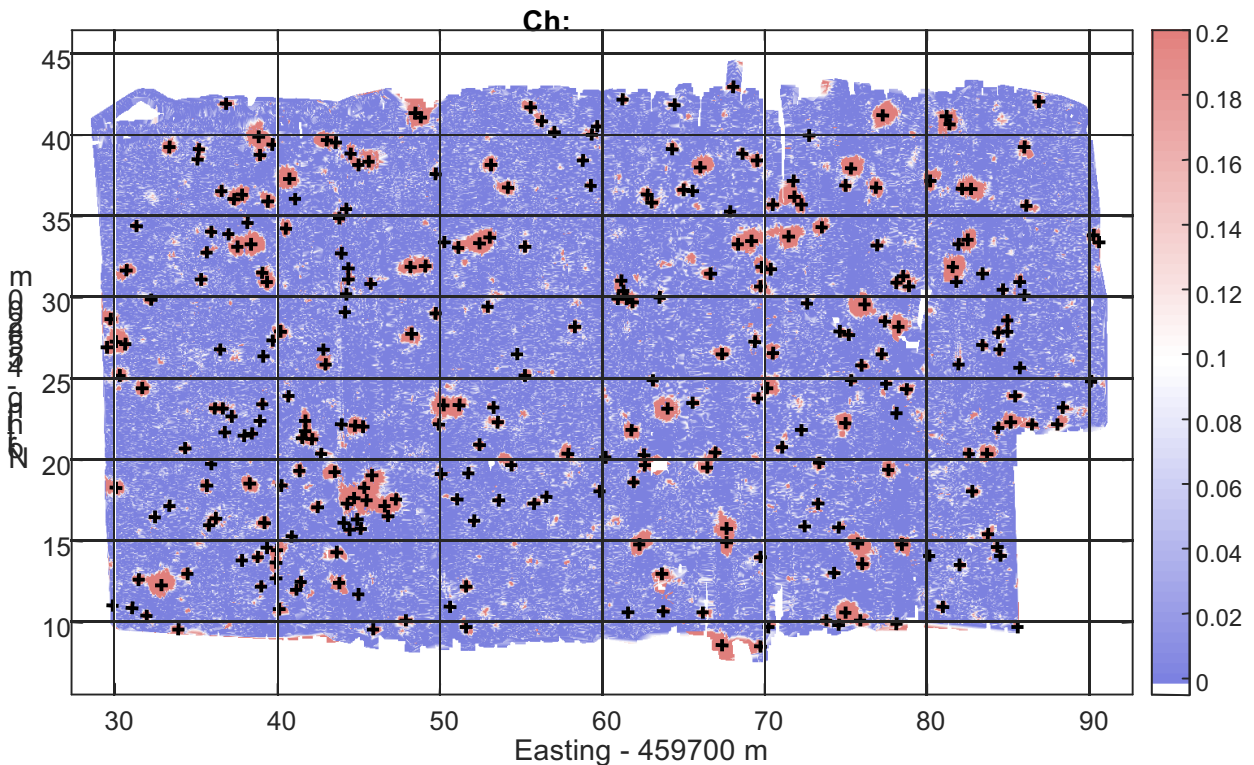


Figure 10: Detection map for the East grid. Black crosses indicate anomaly pick locations.

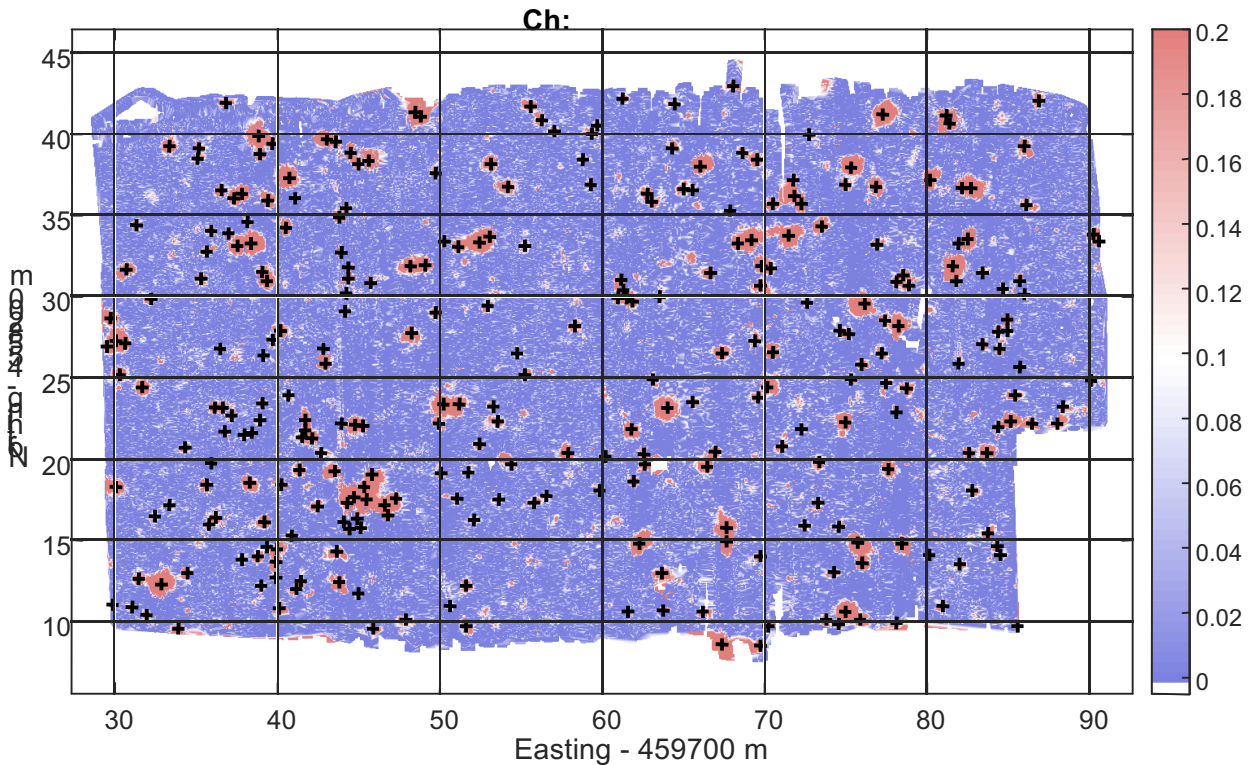


Figure 11: Detection map for the West grid. Black crosses indicate anomaly pick locations.

6.3 PARAMETER ESTIMATION

Classification was based on inversion of cued data. As with previous ESTCP projects, data were processed with BTG's UXOLab, a MatLab-based software developed and tested in numerous SERDP and ESTCP projects. Data were inverted using a three-dipole instantaneous polarizability model (Pasion and Oldenburg, 2001), solving for the potential presence of 1, 2 or 3 underlying sources for every cued location. Decisions regarding the number of targets at a given location were made by prioritizing the most munitions-like models, using the target polarizability decay parameters as the main features for classification. Prior to classification, inversion results were reviewed to identify any potential issues with the data or the inversion output.

6.4 TRAINING

Classification was based on a library matching method. The library of target polarizabilities was compiled from past ESTCP demonstrations. The library was validated by comparing features for small and medium ISO with those extracted from the IVS. No additional, site-specific training information was requested.

6.5 CLASSIFICATION

The classification study was applied to a subset of 498 anomaly locations that were selected by CH2MHill. These consist of 430 TEMTADS picked locations, plus 68 MPV locations that

were further than 0.2 m from TEMTADS picks. Cued data were collected with the MPV for all 513 MPV picks and 430 TEMTADS picks.

The classification method followed standard practices for ESTCP demonstration studies. Classification was based on the recovered set of three polarizability decay parameters. The polarizabilities were matched to a library of polarizabilities obtained by incorporating site-specific available TOI items, and reference polarizabilities from TOI found at previous MPV demonstrations.

Classification produced a ranked anomaly list similar to Figure 12. The first items on each anomaly list are those targets for which reliable parameters cannot be extracted and therefore must be dug. Next come the items that are considered as “high confidence” munitions. Items are ranked according to decreasing confidence that the item is hazardous. Any items that are analyzed without reaching an unambiguous classification decision are placed next on the anomaly list. Finally, all items that are confidently classified as non-hazardous are ranked by their confidence.

Initial Ranked Anomaly List					Final Ranked Anomaly List				
Anomaly ID	Category	Dig on First Pass	Type	Comment		Anomaly ID	Category	Dig	Type
2498	-1	1		Training Data		2498	-1	1	
247	-1	1				247	-1	1	
1114	0	1		Can't extract reliable parameters		1114	0	1	
69	1	1	105			69	1	1	105
811	1	1	48	High likelihood TOI		811	1	1	48
313	1	1	37			313	1	1	37
883	2	1				883	1	1	
1642	2	1		Unable to classify	First Pass Threshold	1642	1	1	
713	2	0				713	1	1	57
406	3	0				406	3	0	
...	3	0		High likelihood not TOI		...	3	0	
...	3	0				...	3	0	
...	3	0				...	3	0	
...	3	0				...	3	0	
...	3	0				...	3	0	
...	3	0				...	3	0	
...	3	0				...	3	0	

Figure 12: Standard format of prioritized anomaly list for an ESTCP demonstration.

7. PERFORMANCE REVIEW

7.1 PRODUCTIVITY

The acquisition times of data files during each day is shown in Figure 13 to illustrate data collection progress during the study. Daily data collection periods were shorter than typical sites due to logistical constraints (site remoteness, time constraints for team members).

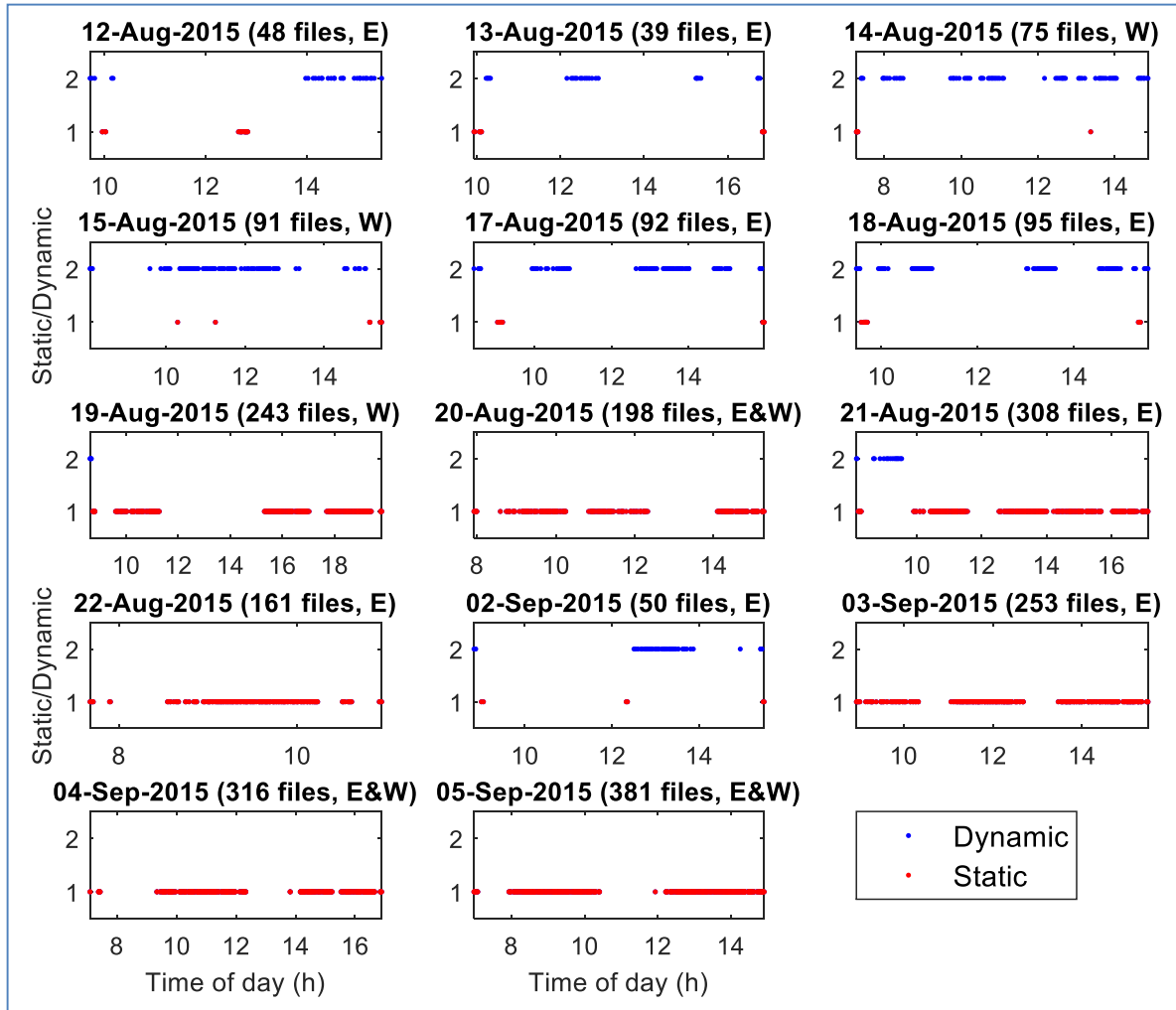


Figure 13: Productivity shown as function of recording of EM data files.
The title indicates the day, number of files and grid name.

The first day (12-Aug-2015) was mostly dedicated to setting up the IVS: identifying a quiet area, collecting background data in dynamic and cued modes, seeding and performing the first IVS survey. In the late afternoon, we tested the dynamic survey on the East grid.

The second day was spent on the East grid, with multiple interruptions due to laying out lines, TEMTADS troubleshooting, and stopping for weather. Longer breaks in the following days were generally due to similar reasons, including several thunderstorms and additional delays when moving the base station to a different control point.

The two grids cover a total of one acre surveyed over the course of 5 days, or an average of 0.2 acre per day. The dynamic data collected on 21-Aug-2015 correspond to recollected lines. The dynamic data for 2 hours on 02-Sep-2015 correspond to filling longer RTS gaps to achieve 100% coverage on the western half of the East grid.

Cued interrogation was performed over all 516 MPV picks and all 430 TEMTADS picks over 6.5 days (or 6 effective days, excluding external delay on Aug 19, but including delays due to moving the base station). This corresponds to an average daily rate of 150 cued anomalies. Practically, 1650 cued data files were collected to cover approximately 900 anomalies. The excess of files is due to recollects, when additional cued measurements were collected over an anomaly as the result of the real-time infield EM3D inversion indicating an offset between the sensor and the predicted target location. This project was the first time that feature was used at a live site, which led to additional recollects whenever the target offset was greater than 10 cm.

7.2 IVS REPEATABILITY

7.2.1 Dynamic data

A measurement objective for the IVS dynamic data was to repeat the detection signal amplitude within a factor 2 for each of the seeded items. The histogram in Figure 14 shows, the distribution of the target response normalized by the mean value for that target, for each of the four IVS items. The target response is defined as the maximum signal recorded on all Z-component receivers for channel 9 (0.95 seconds) within 1 meter of the target location. The target response was obtained for the morning and the evening survey over the IVS. The normalized response varies between 0.5 and 2; therefore, the objective was met.

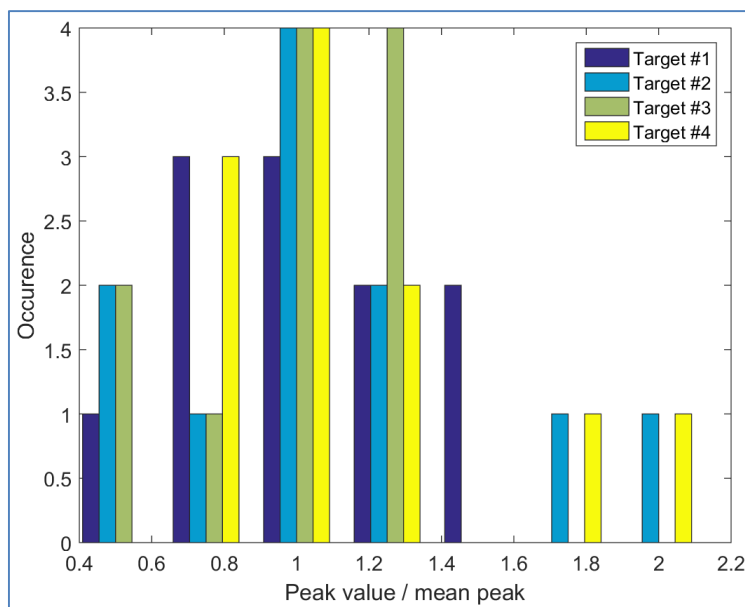


Figure 14: Histogram of the normalized peak amplitude for each IVS pass over each target.

7.2.2 Cued data

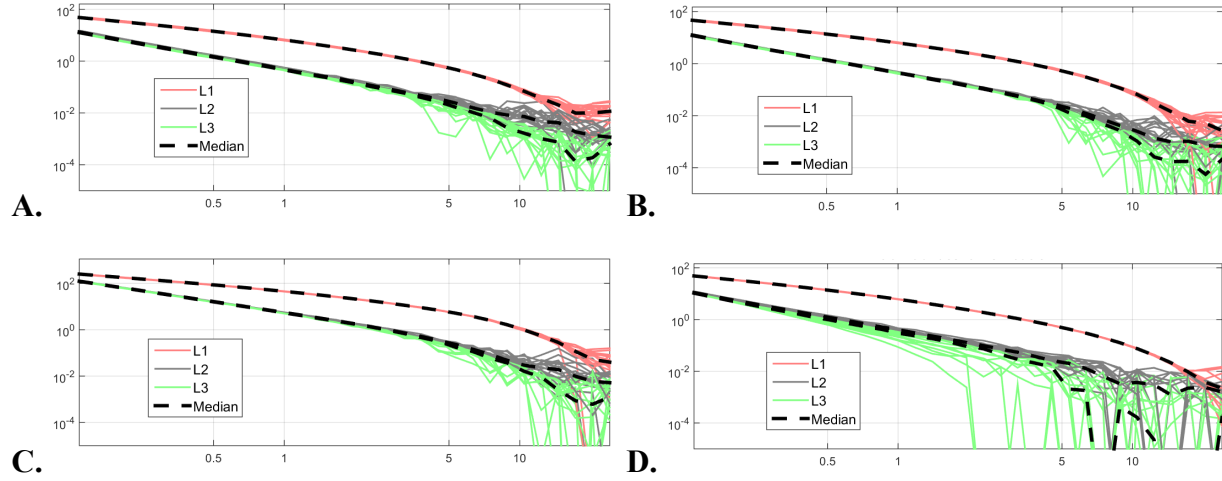


Figure 15: Recovered polarizability decay curves illustrating repeatability of IVS cued data.
Panels A, B and D show a small Schedule 80 ISO, whereas C shows a medium Schedule 40 ISO.

Cued data were collected twice daily and inverted for each IVS target. The recovered polarizability decays are shown in Figure 15. The objective for the static IVS was to recover the size parameter within a factor 1.5. The distribution of the size parameter in Figure 16 shows that the size was recovered within 1.02 for the small and the medium ISO.

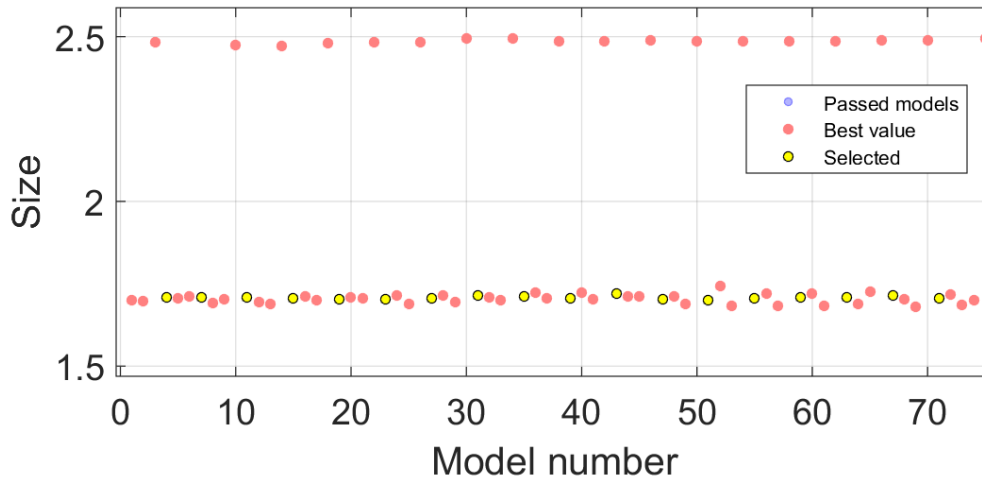


Figure 16: Stability of the recovered size parameter for cued IVS data.
The medium ISO is consistently found at a size of 2.48 ± 0.02 and the small ISO at 1.71 ± 0.03 .

7.3 CLASSIFICATION WITH CUED DATA

Classification was applied to 498 anomalies that were subsequently excavated. The anomaly locations were based on picked locations for all 430 TEMTADS targets and 68 MPV targets. Classification of each anomaly was achieved by inverting all cued data files acquired within 0.5 m of the target pick. Inversion was performed for one, two and three sources. After examination of the recovered polarizabilities, the analyst determined that no training data was required, based on the fact that standard targets were present at the site.

The stage 1 dig list was submitted to the ESTCP for scoring, using a conservative stop dig point to account for cases where the acquired sounding was not collected at the optimal location relative to a target of interest, which could lead to non-optimal recovery of the target parameters. The scoring result for that first dig list is illustrated in Figure 17 with Receiver Operator Characteristic (ROC) curve, which shows the number of non-TOI to be excavated to recover all TOI up to the defined stop dig point.

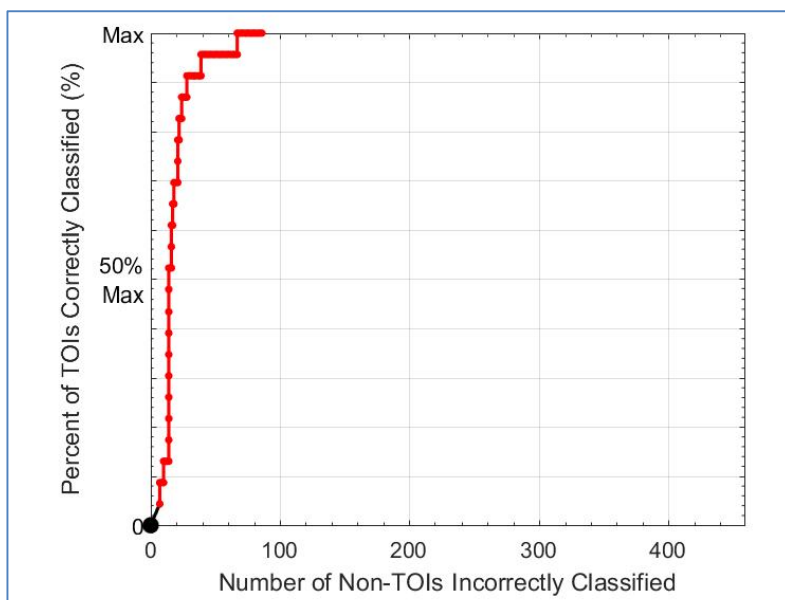


Figure 17: ROC curve for stage 1 dig list.

Examination of the ground truth information for the items marked for excavation in stage one revealed multiple problems in the scoring file:

- Several items that had the highest probability of being a TOI did not have a dig result within a close distance, and the dig result was shifted to the North (targets ID TH-10635, 10570, 10138, 10154, 10248, 10563, 10516, 10519, 10057, 10561, 10252, 31021), the East (10169), the West (10184) or the South (10045). This suggested that either the TOI identified by the MPV had not been excavated, even though some of these targets corresponded to high likelihood seeded ISOs (Figure 18), or the dig results were associated with an incorrect target label.
- Items were incorrectly categorized as munitions debris instead of TOI (TH-10069 and 10248).

- Reported MPV pick locations were shifted by 0.5 m relative to originally provided locations.
- Small debris was reported at a location where an ISO seed was missed at the detection stage.

On the basis of these problems, we considered the ground truth data to be unreliable for scoring. As a consequence, the analyst submitted a stage 2 dig list where all items were listed for excavation. The dig list was similar to the first one, with the difference that the problematic targets listed above were moved to an earlier position on the dig list, right after the stop dig point of the first list. This ensured that if these were indeed labelled as TOI, they would still appear early in the final ranked dig list.

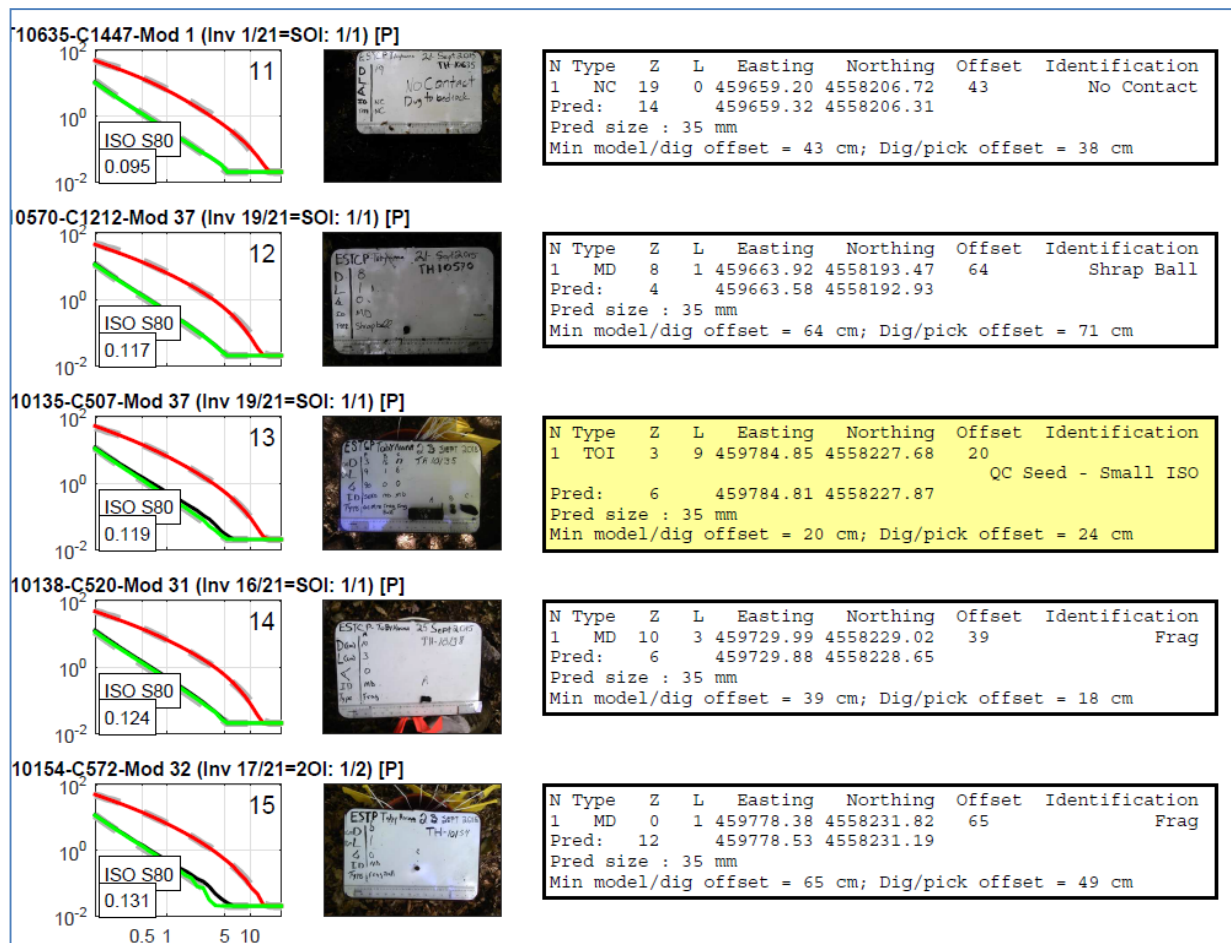


Figure 18: Example of ground truth report for items ranked 11 to 15 in the dig list.

The left panels show the recovered polarizabilities for item (rank in top right number in panel), which here have high likelihood matches to a small Schedule 80 ISO. The central panels show the ground truth photos. The right panels show the ground truth information, in particular the offsets between the model, the pick and the dig locations. There are significant dig/pick offsets in these examples.

The complete ground truth information confirmed our assumption that some dig locations had been shifted and attributed to the wrong target label. In particular, we found that:

- The dig location associated with target TH-10655 was much closer to target 1035, which corresponded to an early dig (Figure 19). Similarly, we found the following pairs: 10568/10570, 10519/10516, 10150/10154, 31039/10138 and 31011/10169.
- Three dig locations were associated with IVS targets (TH-10001, 10002, 10233).
- In general there were large offsets between the pick location and the dig location, as shown in Figure 20. There was no particular bias direction for the TEMTADS picks, whereas the MPV were offset to the North (producing a discrepancy with actual MPV picks, as noted earlier).

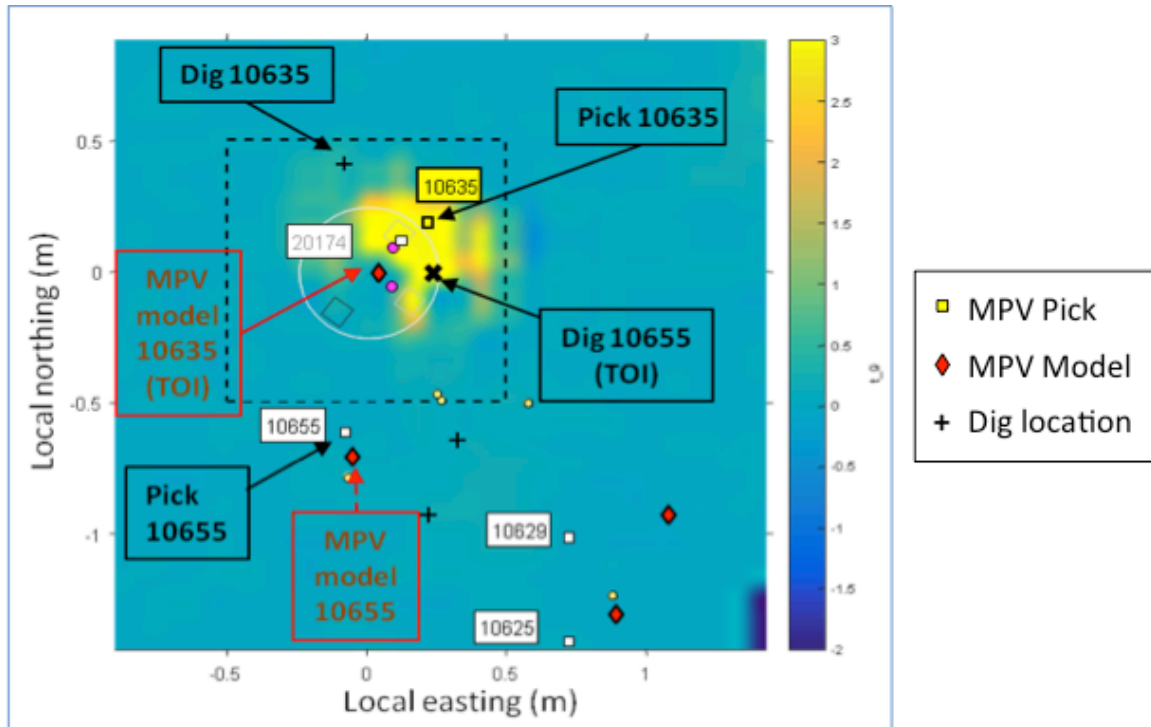


Figure 19: Pick, dig and predicted locations for nearby targets TH-10635 and 10655. Target TH-10635 was predicted to be a high likelihood TOI through classification (Dig #11). The background map shows the MPV detection data. The pick location for 10635 is indicated with a yellow square, just below its yellow label, while the predicted model location is a red diamond marker located 20 cm to the Southwest (exactly at the center of the MPV, indicated with a white outline). The dig location associated with TH-10635 is the black cross mark (+) located to the Northwest. The thick black X marker located 0.2 m directly to the South of the 10635 pick is the dig location that was associated with target 10655, for which a TOI was excavated. The pick location for TH-10655 is located 0.7 m to the Southwest of its associated dig location (the nearby MPV model corresponds to a low likelihood target). The map suggests that the TOI dug under label 10655 is much closer to the pick location of 10635 and should be used as ground truth for target 10635.

The scoring file was modified by setting the targets pairs identified above as the same target (although the picks were generally half a meter apart), removing the three targets where digs were associated with IVS locations, and correcting the other labelling issues noted above. The dig list was scored using this corrected reference file. The result is presented in the ROC curve in Figure 21, which shows that all TOI were efficiently identified in the dig list. The last TOI was found after digging only 7% of the TOI, while the original stop dig point achieves 83% clutter rejection.

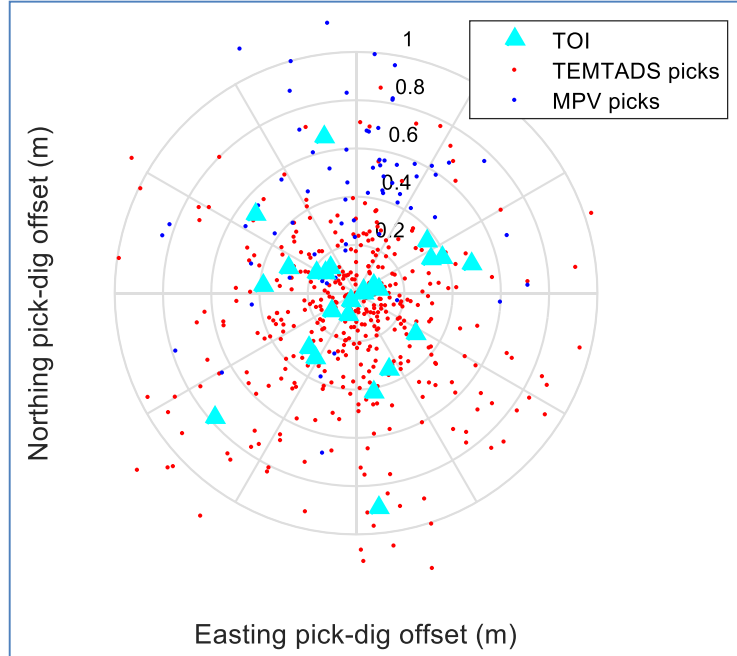


Figure 20: Positioning offset between pick and dig locations reported in ground truth file.

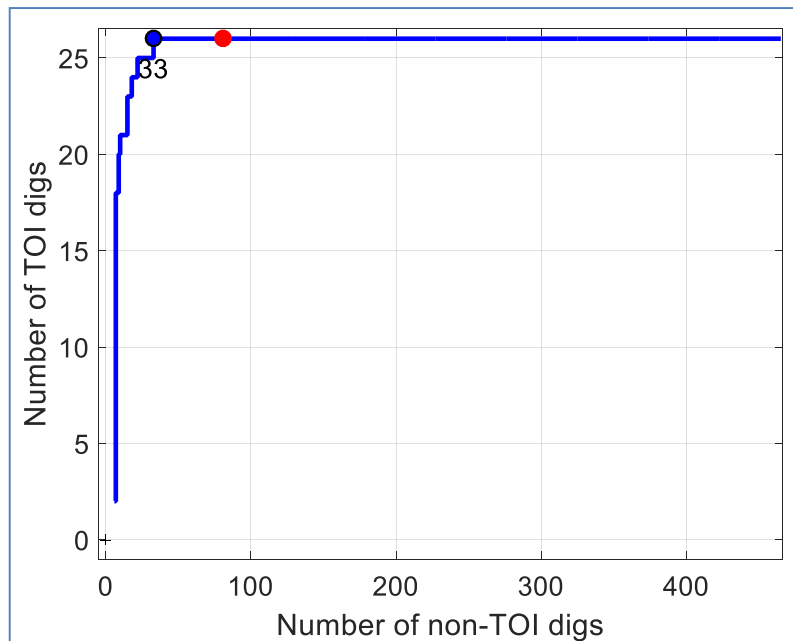


Figure 21: MPV classification ROC curve with corrected ground truth at Tobyhanna. Blue marker indicates point at which all TOI are identified, and red marker is the stop dig point for our initial submission.

7.4 POSITIONING ACCURACY

The forested Tobyhanna site caused positioning challenges for all stages of the project. Accuracy for positioning detected anomalies, reacquisition for cued interrogation, and validation by excavation was affected by positioning problems. As noted in the previous section, this also created issues with associating the correct labels for picks and dig locations. After resolving the most obvious issues, we found that:

- For TOI, the median positioning error relative to dig locations is 13 cm for MPV classification models, 16 cm for MPV dynamic data picks, and 26 cm for TEMTADS dynamic data picks. For all objects longer than 5 cm, the corresponding median positioning errors are 19, 20 and 24 cm, respectively.
- The median error in depth is 3 cm for all TOI and 3.5 cm for all items longer than 5 cm, with 96% of TOI and 73% of all items longer than 5 cm being predicted within 15 cm depth.

8. COST ASSESSMENT

Time and resources were tracked for each task to assess the cost of deploying the technology at future live sites. A cost model is presented in Table 3. It assumes an hourly rate of \$100 and accounts for 14 days in the field, while there were 11.5 effective days of data collection. We include a contingency of two days to account for working at a remote site with slow RTS setup, delays due to the presence of two teams and weather interruptions

Data collection involved two geophysicists and occasional help from a third person for relief and support (e.g., laying out survey ropes, fetching supplies, etc.). In practice, the project geophysicist filled the support role while also processing data on site. The dynamic data analysis was more intensive than usual due to the challenges associated with processing RTS data. The task of re-interpreting the data after the missed detection is included in data processing time; the time spent preparing the RCA is not included here.

Table 3: Cost model for the MPV demonstration.

Cost Element	Data to be Tracked	Units	Sub-total	Total cost
Survey cost				
Pre-survey activities	Hours for: <ul style="list-style-type: none"> Demonstration plan and coordination Sensor preparation and verification Special RTS testing and data analysis, programming of interpolation algorithm for RTS interruptions in coverage 		60 h 16 h 80 h	\$15,600
Mobilization and miscellaneous costs	Cost and hours for <ul style="list-style-type: none"> Return packing and shipping RTS rental Mobilizing 3 people Meals and accommodation: 3 person, 15 days Car rental (sport utility vehicle) 	\$1,000 \$1000/week 8 h \$200/day \$1200/week	\$2,800 \$2,000 \$5,400 \$9,000 \$2,400	\$19,600
Instrument setup	Hours to set up and calibrate for 2.5 person: <ul style="list-style-type: none"> Bring MPV to remote site, unpack, assemble and setup for survey Prepare IVS and perform initial survey Analysis 	4 h 6 h 6 h	10 h 15 h 6 h	\$3,100
Detection survey 1 acre in 7 days	Unit: cost of collecting data with 2.5 person <ul style="list-style-type: none"> Daily access, setup and IVS Collection time for dynamic survey Contingency Data QC time 	3 h/day 5 days 2 days	52 h 75 h 24 h 20 h	\$17,100
Cued survey: 950 anomalies in 7 days	Unit: cost of collecting data Personnel: 2.5 <ul style="list-style-type: none"> Daily access, setup and IVS Survey time per cued anomaly Contingency Data QC time 	3 h/day 25 / h 2 days 50 /h	52 h 75 h 24 h 20 h	\$17,100

Data processing				
Detection (1 acre)	Unit: Time for one geophysicist <ul style="list-style-type: none"> • Import dynamic data, process positions, filter EMI data and prepare grid maps • Determine anomaly selection threshold and pick anomalies • Prepare cued data acquisition path 	3 days 1 day 1 h	30 h 10 h 2h	\$4,200
Classification (500 targets)	Unit: Time for one geophysicist <ul style="list-style-type: none"> • Time for reviewing backgrounds and setting up inversions • QC inversion results • Test classifiers and TOI library, training data • Apply classifier, review and submit dig list and assimilate ground truth 		10 h 30 h 40 h 20 h	\$10,000
Total cost				\$86,700

9. MANAGEMENT AND STAFFING

A flow chart of the organizational project structure and the relationships between the project roles is shown in Figure 22.

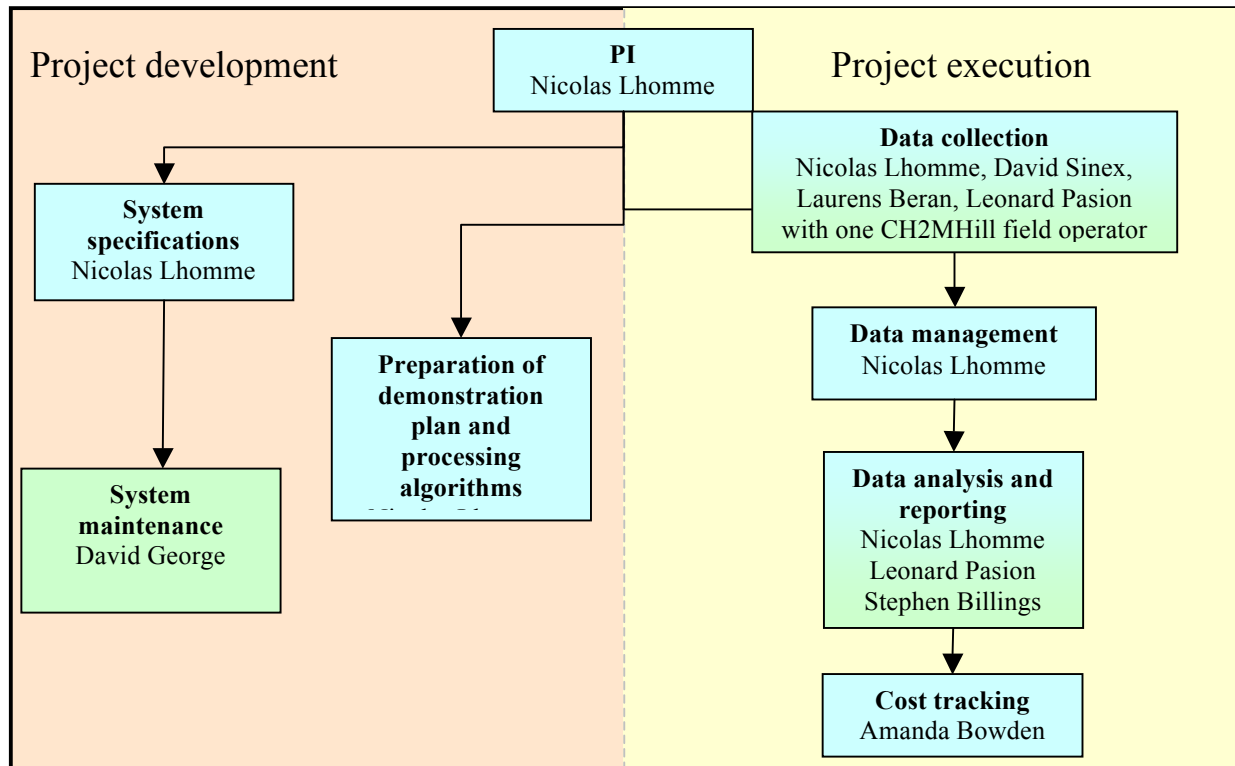


Figure 22: Project management organization for the demonstration.

The demonstration was led by Nicolas Lhomme (PI, BTG), acting as project geophysicist in charge of preparing the demonstration plan, scheduling, coordination, logistics, training and field operation. Data collection was split in two deployments that each involved two BTG personnel (Nicolas Lhomme, David Sinex, Laurens Beran and Leonard Pasion) and support from Vicki Rystrom of CH2M. Upon first arrival on site, BTG personnel assembled the equipment, reviewed standard operation procedures (SOP) for collecting MPV data with RTS positioning and adjusted these to the local conditions, where trees and deadfall were creating obstacles for positioning and for following lines. The CH2M field crew was then trained to operate the sensor for dynamic data collection. The PI reviewed and processed all data on and off site. In particular, morning IVS data were immediately processed and validated. Dynamic data were processed and targets were picked during the first deployment so that cued collection of MPV picks could immediately follow. Cued data were controlled for quality and coverage and anomalies that required additional soundings were reacquired. The second deployment involved Pasion and Sinex and consisted of a couple of hours of dynamic data collection to ensure 100% coverage on half of the East grid, and cued data collection over target picks that were specific to the TEMTADS2x2. A root cause analysis report was prepared by Lhomme, Pasion and Billings for one seed item that was missed at the detection stage. Classification was performed at a later stage on a subset of 498 targets, followed with reporting.

10. REFERENCES

- Barrowes, B.E., O'Neill K, George, D.C., Snyder, S., Shubitidze, F. and Fernandez, J. P., Man-Portable Vector Time Domain EMI Sensor and Discrimination Processing. SERDP 1443 FY07 Annual Report, 2007.
- Billings, S., Pasion, L., Lhomme, N. and Oldenburg, D., Discrimination at Camp Sibert using Time-Domain EM. SERDP/ESTCP Partners in Environmental Technology Symposium, Wash., DC, Dec. 2007.
- Lhomme, N., Demonstration of MPV Sensor at Yuma Proving Ground, Arizona. Demonstration Report. ESTCP Project MR-201005, 2011.
- Pasion, L. & Oldenburg, D., A Discrimination Algorithm for UXO Using Time Domain Electromagnetics. Journal of Engineering and Environmental Geophysics, 28, 91-102, 2001.

APPENDICES

11. Appendix A: Health and Safety Plan (HASP)

Health and safety procedures followed the CH2MHILL plan for this demonstration.

12. Appendix B: Points of Contact

Points of contact (POCs) involved in the demonstration and their contact information are presented in Table 4.

Table 4: Points of Contact for the MPV Demonstration.

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone E-mail	Role in Project
Dr. Nicolas Lhomme	Black Tusk Geophysics 401-1755, W Broadway Vancouver, BC V6J 4S5, Canada	Tel: 604-428-3382 Nicolas.Lhomme@btgeophysics.com	Project PI
Dr. Stephen Billings	Black Tusk Geophysics 401-1755, W Broadway Vancouver, BC V6J 4S5, Canada	Tel: 720-306-1165 stephenbillings@btgeophysics.com	Project PI
Tamir Klaff	CH2MHill 18 Tremont St Suite 700 Boston , MA 02108	Tel: 202-596-1199 Tamir.Klaff@ch2m.com	Industry Partner
Dr. Herbert Nelson	ESTCP Program Office 4800 Mark Center Drive Suite 17D08 Alexandria, VA 22350-3605	Tel: 571-372-6400 herbert.h.nelson10.civ@mail.mil	ESTCP Program Manager

13. Appendix C: Root Cause Analysis for a missed seed in the MPV detection study

Summary

A quality control (QC) seed item was not included in the initial Man Portable Vector (MPV) derived detection list submitted for the Tobyhanna ESTCP Live-Site demonstration study. The primary cause for the missed QC seed was the use of overly aggressive criteria for selecting anomalies. A contributing factor was positional errors arising from the use of a Robotic Total Station (RTS) system for positioning in the difficult wooded environment at Tobyhanna. This memo provides an overview of the target picking approach, identifies causes for the missed seed, and specifies the corrective action taken.

Initial processing

A QC seed was missed in the initial detection analysis of the MPV data collected at the Tobyhanna demonstration site. Dynamic MPV data were positioned using an RTS laser positioning system and an attitude heading and reference system (AHRS). Data were acquired over the East and West grids during a period from Aug 12 - Sept 2, 2015.

A data amplitude-based target picking algorithm applied to the profile data (not the gridded data) was used to detect anomalies. The detection algorithm was applied to Z-component data from all receiver cubes. The 0.95 millisecond (ms) time channel was selected in order to reduce picks due to fast decaying clutter (i.e. targets with a time constant less than 1 ms) while being early enough in the time decay to maintain a sufficient signal to noise ratio for detecting potential targets of interest (TOI). Data from each receiver were treated as a separate profile, with anomalies picked along each profile. A detection threshold of 1 mV/A was chosen. A minimum anomaly "footprint" size criterion was used to reduce the number of anomalies due to small, near surface clutter or noise. The footprint size required that the detection threshold be exceeded over three consecutive measurements along a line, and that anomalies appeared on at least two receiver profiles. The detection threshold and footprint size were chosen by the analyst because it appeared to identify distinctive anomalies while rejecting small, localized anomalies.

Root Cause Analysis

A gridded image of the data used for picking is presented in Figure 23. The image focuses on the region near the missed seed, which is located near the center of the image (white star at x=78.5 m, y=31.2 m). The MPV receiver tracks are indicated by black dots, with the track passing over the seed highlighted in yellow. The seed location is indicated by a white star.

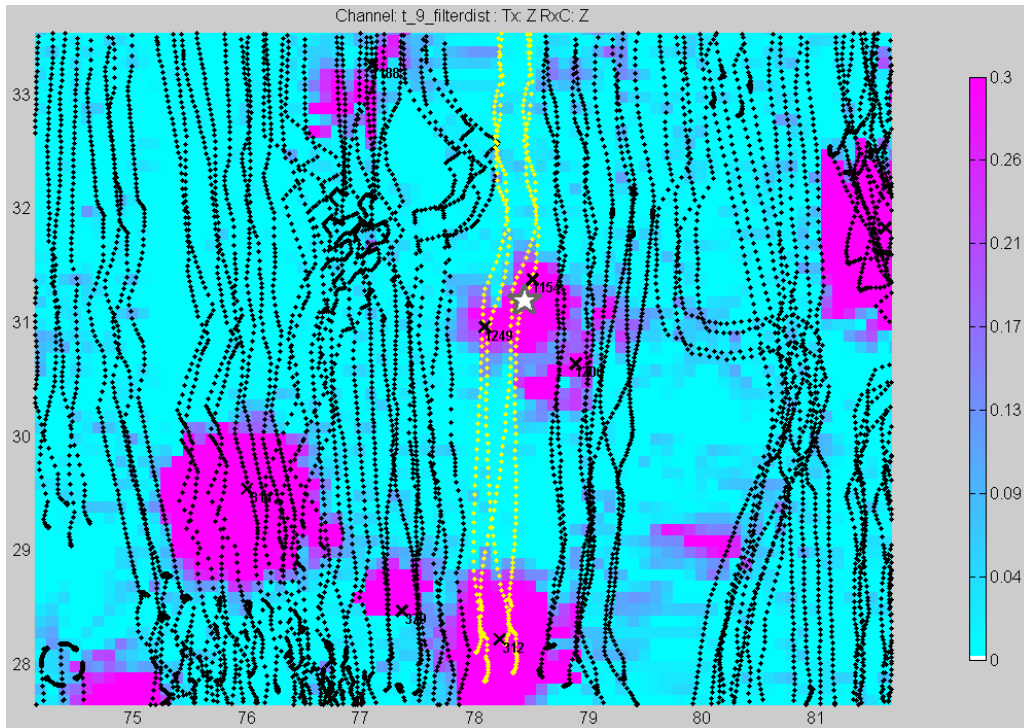


Figure 23: Gridded data for Z-component of the 0.95 ms time channel around missed seed (marked with a white star). The image is based on the original data that were used for target picking. The track over the seed location is marked with yellow dots. The other tracks are indicated with black markers.

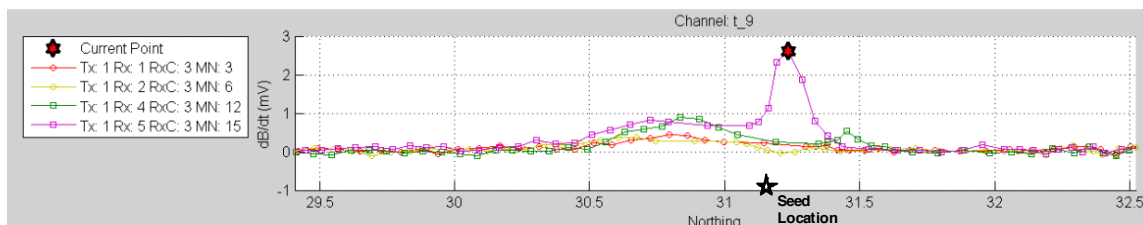


Figure 24: Signal for Z-component data at channel t_9 (0.95 ms) on line profile going through seed location (yellow line in Figure 24). The magenta line shows signal above the threshold and corresponds to cube #5, the closest to the operator. The location of the seed is at a local Northing value of 31.16m.

The line profiles for each of the receivers as the MPV passed over the seed are shown in Figure 24. Receiver 5 passed closest to the seed, and recorded a distinct profile peak of approximately 2.5 mV. The remaining receivers record a lower peak approximately 0.4 m to the south of the reported seed location. The profiles in Figure 24 indicate two factors that lead to the missed seed:

- (1) The first anomaly (visible on receiver 5) was not selected due to the requirement to have the threshold exceeded on two profiles; and
- (2) The second anomaly (visible on multiple receivers) was not selected as the amplitude was less than the threshold selected for detection.

Root Cause: The root-cause of the missed QC seed was an ineffective target picking strategy that did not take into account the minimum threshold required to detect the targets of interest and which enforced an additional condition requiring the anomaly threshold to be exceeded on at least two lines.

Corrective Action

Best practice is to set a detection threshold based on the minimum signal expected from the smallest target of interest at the specified clearance depth. In the absence of clear guidance on the smallest TOI, an alternative strategy is to use five times the Root-Mean-Square (RMS) of the noise in the sensor data. MPV noise levels were estimated by analyzing data collected over the East and West grids. The median absolute deviation of the noise for the z-component, 0.95 ms time channel data was calculated to be 0.07 mV/A. We note that the median absolute deviation is a robust estimator of the RMS error. Five times the noise level results in a threshold of 0.35 mV/A.

In order to avoid picking isolated noise-spikes we also implemented a requirement for the minimal spatial extent of the anomaly and developed a strategy to account for the potentially higher signal amplitudes on the outer receiver cubes. To provide an objective basis for the new target picking strategy we utilized the Survey Modeller Tool developed by Black Tusk Geophysics under SERDP Project MR-2226 (Figure 25). For the modeling we utilized a schedule 80 ISO at 25 cm depth and assumed the MPV sensor head was 15 cm above ground.

In general, a detection threshold represents the minimum amplitude signal that can be measured for a TOI. For a rod-like, axi-symmetric target, the threshold corresponds to the signal measured when the MPV moves directly over a horizontal target that is perpendicular to the direction of travel (i.e., the target is oriented cross-track). An anomaly visible in only one profile typically corresponds to a target located beneath the outer edge of the MPV or outside the MPV footprint. For a target beneath the outer edge of the MPV, the signal is larger relative to the signal for a target directly beneath the MPV. There are two primary reasons for this: (1) The primary polarizability is null-coupled to the MPV when a horizontal target is directly beneath the MPV's horizontal Tx loop, and (2) The outer receiver is close to targets located beneath the edge of the MPV.

The curve under the heading “Orientation Responses” in Figure 25 shows how the target response changes as a function of cross track position for an ISO target at a depth of 25 cm and assuming an instrument height of 15 cm. The minimum target response computed for all possible target orientations is approximately four times larger when the target is located under a side cube than when it is located at the center; the response decreases as the target moves out of the sensor footprint and reaches twice the amplitude when the target is offset by 40 cm from the center of the sensor. Based on this analysis, it is consistent to require targets beneath the edge of the instrument to have a higher threshold than for targets that are directly beneath the center. **Therefore, we modified the target picking approach to require that, for anomalies appearing only on a single profile, at least one datum must exceed twice the 0.35mV/A threshold.**

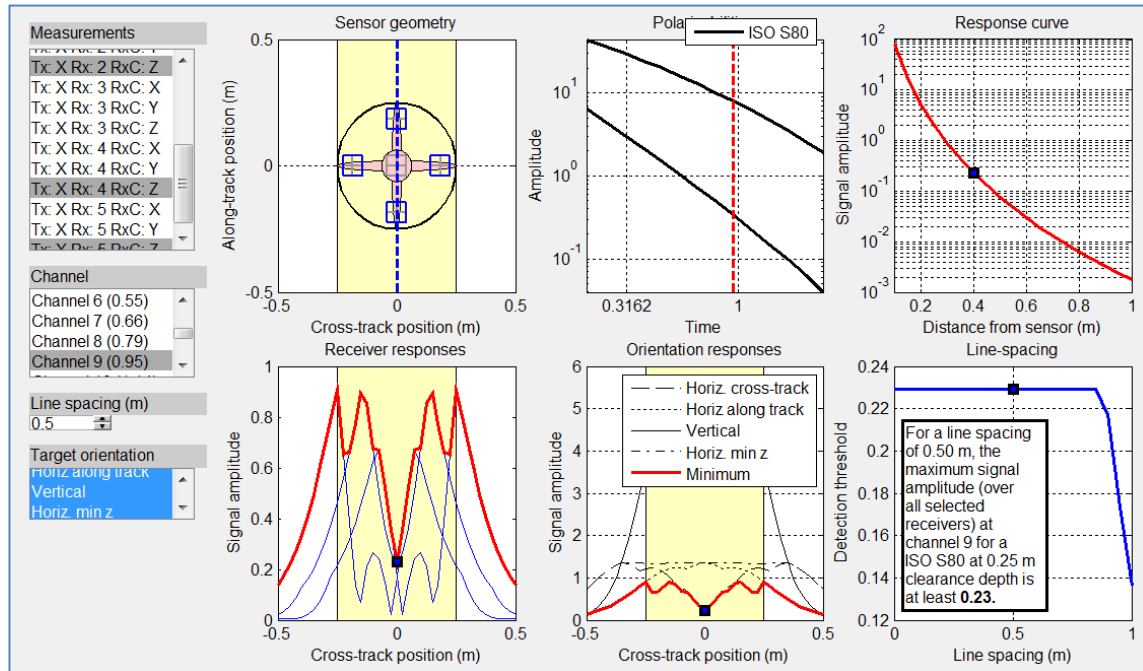


Figure 25: Detection modeller results for the MPV above a small ISO schedule 80 located at 0.25 m below ground with a sensor clearance of 0.15 m.

In Figure 26 we show the output from the UXOLab detection modeller for different along track locations for a small ISO in its worst case orientation. The lowest signal amplitude occurs when the sensor passes over the ISO item and the transmitter and ISO item have minimum coupling (the primary field is orthogonal to the long axis of the ISO and only activates the secondary polarizabilities). Note that for any target offset curve that the minimum signal amplitude at an along track position of 0 m (sensor head in-line with the ISO item) is approximately the same as the signal amplitude a further 0.25 m down the sensor track. The amplitude at along track offsets of 0 and 0.25 m are approximately 20% less than the maximum amplitude measured along the track. This means that instead of using an anomaly selection criterion based on exceeding the maximum signal level we can require that the signal exceeds 80% of the maximum value for 0.5 m distance along track. This criterion reduces our original 0.35 mV/A to 0.28 mV/A which we increased to 0.3 mV/A. We also incorporate an additional safety margin by relaxing the along-track threshold distance from 0.5 m to 0.3 m.

Modified target picking strategy

Targets are selected when either of the following two conditions are met:

- 1) The amplitude of the Z-component data at the 0.95 ms time-channel exceeds 0.3 mV/A on two receivers over a distance of 30 cm along each profile;
- 2) The amplitude of the Z-component data at the 0.95 ms time-channel exceeds 0.3 mV/A on at least one receiver over a distance of 30 cm along a profile AND at least one datum exceeds a value of 0.7 mV/A.

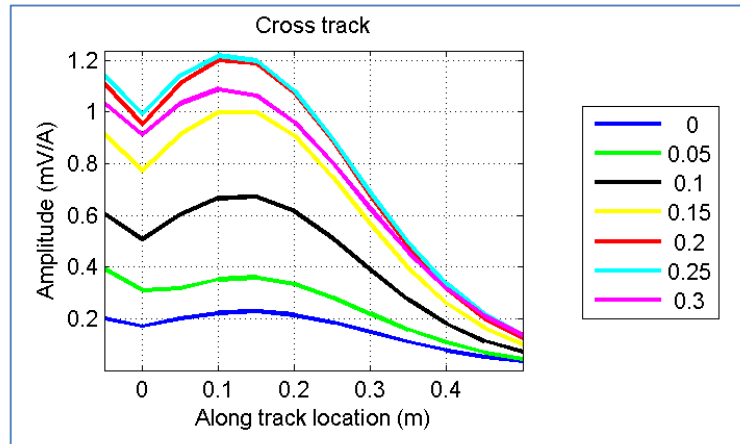


Figure 26: Maximum signal amplitude among all MPV receivers as a function of the sensor location along track relative to a target placed at different cross-track offsets (colored curves), in the worst target orientation for detection (horizontal, across track).

Additional issues identified when conducting this RCA

While sensor positioning issues did not directly result in the missed seed item, they have the potential to result in missed detections. The trees – both fallen and upright – on the Tobyhanna site introduced challenges for data collection and accurate sensor positioning. Although string lines were laid on the ground to assist field crews with navigation, maintaining consistent line spacing was difficult due to walking over or around small boulders and trees (Figure 27). Maintaining consistent line-of-sight between the RTS “gun” and sensor prism was not possible, resulting in frequent loss of lock with the RTS.



Figure 27. Tobyhanna East grid. View from IVS on South edge of grid towards the Northwest corner.

Corrections of the RTS positions were insufficient in the original processing due to a series of unexpected positional issues associated with this environment that had not been fully resolved at

the time of the initial target picking (e.g., false RTS updates). As part of the process followed in this RCA, the position processing methods for selecting the correct RTS updates and interpolating the positions were reviewed and improved. The main improvement was the treatment of false position updates after dropouts, which resolved the false across line segment north of the seed and cases where the RTS produced a new time update using a past location, which confounded the original interpolation method. The identification of periods where the sensor was stationary was also improved, which allowed for better interpolation of positions between RTS dropouts.

Our demonstration report contains details of the improvements in positional processing methods and some of the challenges encountered. For the purpose of this RCA we note that the location of some anomalies locations was sensitive to the revised positional correction method. For instance, running the original detection algorithm at an adjusted 0.3 mV/A threshold produces 365 anomalies with the original data and 361 anomalies with the updated corrections. These anomalies relate to exactly the same EMI data and differ only in the assigned locations. There are only 271 common locations between the two datasets, assuming a tolerance of 0.3 m for common picks (306 common at 0.4 m tolerance). The remaining 90 anomalies are low amplitude ones that only appeared on one sensor track and migrated location after positional corrections were improved. Thus, while deficiencies in the original positioning method did not cause the missed seed they had to be remedied in order to avoid missing additional items.

Lessons learned

The threshold definition should always follow an objective, defensible method and be reassessed when the data are modified. Once data are correctly located and processed, the threshold should be derived from noise analysis when a detection objective is not set, or from an output of the detection modeller, when the clearance depth and target of interest are defined.

While this ESTCP demonstration did not fully replicate the conditions of a production project, Black Tusk Geophysics acknowledges that it should have conducted an internal quality assurance check on the procedures utilized by the data analyst working on the MPV data. Such an internal check would have revealed that the target picking threshold and strategy were arbitrarily chosen by the analyst and not supported by objective analysis.

New site conditions and use of technologies that have not been extensively tested can bring unexpected challenges. In preparation for this study we rented an RTS and tested it on an IVS with trees. Some of the positioning issues did not arise, perhaps because we had rented a higher end RTS model, but most likely because testing was limited in space and time and could not trigger the conditions that caused issues. Through the execution of this demonstration project, the RTS system and associated positional methods have been exercised and thoroughly tested. The improved processing methods developed and the experience gained through this project should prevent a repeat of the identified problems when the technology is applied at a production location.